FAULT IDENTIFICATION MATRIX IN LINEAR NETWORKS

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THESIS

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ABSTRACT

A method utilizing vector representation is investigated for determining a faulty element in passive and active networks by simple external measurements.

A large system may be considered as an interconnection of a number of subnetworks. By utilizing the relationships between the magnitudes of a transfer function at various frequencies and the deviations of a circuit element, the fault simulation curves can be drawn. The fault identification regions are defined from the fault simulation curves. A fault identification matrix is constructed corresponding to the defined fault identification regions.

The fault identification matrix, when premultiplied by a vector whose components are measured from a network, yields another vector whose components identify a network element which is faulty.

A test procedure for the fault identification method is presented and verified by experiments.

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I. INTRODUCTION

Recent advances in the design of electronic systems have resulted in an ever-increasing complexity in such systems. Despite the advances in component reliability and preventive maintenance, it appeared that a great many unpredictable or random failures do occur. Such complexity in modern equipments used by the industry and the military has resulted in a serious problem of providing adequate maintenance. One of the most difficult tasks is the location of malfunctions which, until recently, has been left entirely in the hands of technicians.

Some techniques for fault identification have been studied by a number of investigators [1,2,3,5,6,7,8,9,10] and a computer program for fault simulation of passive linear networks without mutual inductance has been given in Ref. [2].

In this paper, the problem of fault identification, which requires the least number of external test points of the system, is investigated and a procedure which will automatically identify a fault or faults in passive and active linear networks is presented. Toward achieving this ultimate goal, the sensitivity of a network function due to element deviations is studied. The method, which requires matrix operations, is introduced. In this method, the fault identification regions at a set of selected test frequencies are defined depending on the network sensitivity and the fault identification matrix is generated. A vector is then obtained by premultiplying the fault identification matrix by another vector, and the resulting vector identifies the fault.

The single element fault identification method is discussed and the combined element fault identification method is introduced by utilizing the single element fault identification method.

The computer programs, which identify a fault element in a properly partitioned network, using the proposed method are written in FORTRAN IV and included in Appendix A. The implementation of the computer programs is annexed in Appendix B.

II. PRELIMINARY CONSIDERATIONS

A. DEFINITION OF A VECTOR

Consider a two-port network with the external terminals and variables as defined in Fig. 2-1. The forward voltage ratio transfer function,

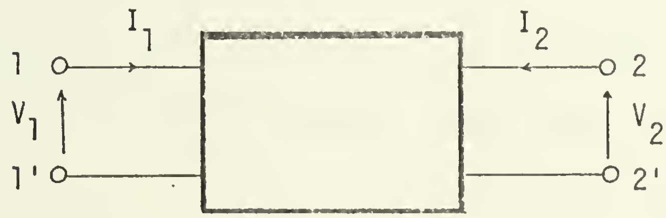


Fig. 2-1.

2-port network.

T12, is defined as the ratio of the output voltage to the input voltage with the output current set to zero.

$$T12 = \left. \frac{V_2}{V_1} \right|_{I_2=0} \qquad (2\text{-}1)$$

The magnitude of T12, designated by $|\dot{T}12|$, is given by either a function of the frequency with fixed element values or a function of an element value with a fixed frequency. That is, at a set of n frequencies, with fixed element values, a set of n different magnitudes of a transfer function, T12, can be obtained. Similarly, corresponding to a set of k deviations of an element value, with a fixed frequency, a set of k different magnitudes of T12 can be determined.

Let the network contain only the following types of passive elements: resistors, inductors and capacitors. Consider an element which has a nominal element value E with a deviation designated by ΔE_j , where the subscript j implies the j-th deviation.

With a change in element value ΔE_j of E, n values of $|T12|$ can be obtained corresponding to n different frequencies. These values of $|T12|$ are designated by

$$|T12|_{j1} \ , \quad |T12|_{j2} \ , \quad --- \ , \quad |T12|_{ji} \ , \quad --- \ , \quad |T12|_{jn}$$

where the first subscript indicates the j-th deviation and the second subscript indicates the i-th frequency. Next, with a nominal element value of E, n values of $|T12|$ can be obtained corresponding to n different frequencies and designated by

$$|T12|_{01} \ , \quad |T12|_{02} \ , \quad --- \ , \quad |T12|_{0i} \ , \quad --- \ , \quad |T12|_{0n}$$

The normalized value of $|T12|_{ji}$ is defined as

$$\frac{|T12|_{ji}}{|T12|_{0i}}$$

where $i = 1, 2, --- , n$.

For example, with a deviation ΔE_j of E and a set of 5 frequencies, the 5 values of the normalized $|T12|_{1i}$ are

$$\frac{|T12|_{11}}{|T12|_{01}} \ , \quad \frac{|T12|_{12}}{|T12|_{02}} \ , \quad ---------- \ , \quad \frac{|T12|_{15}}{|T12|_{05}}$$

With another deviation, ΔE_2, of E and the same set of 5 frequencies, the 5 values of the normalized $|T12|_{2i}$ are

$$\frac{|T12|_{2i}}{|T12|_{01}} \ , \quad \frac{|T12|_{22}}{|T12|_{02}} \ , \quad ---------- \ , \quad \frac{|T12|_{25}}{|T12|_{05}}$$

Let a vector $\overline{X}$ be denoted by

$$\overline{X} = (x_1, x_2, --- , x_i, --- , x_n, c)' \tag{2-2}$$

where $\overline{X}$ is an array of the n normalized values of $|T12|$ with respect to a set of n frequencies (with a deviation of ΔE_j) and a constant c; x_i denotes $\frac{|T12|_{ji}}{|T12|_{0i}}$ $(i = 1,2, --- , n)$ and c is unity;

$\overline{X}$ is n dimensional because the last component is always unity; the superscript (') means a transpose of an array of $\overline{X}$ or a matrix.

B. CONSTRUCTION OF FAULT IDENTIFICATION MATRIX AND GENERATION OF VECTOR-Z

Consider a simple two-port network that contains a resistor, R, and a capacitor, C, as shown in Fig. 2-2. Let the nominal value of R be 1 ohm and that of C be 1 farad. The value of C can be changed from

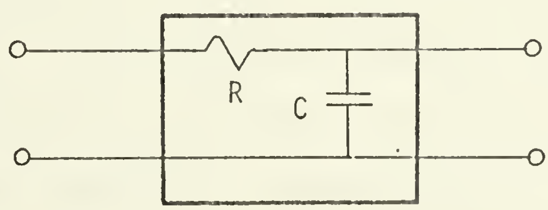


Fig. 2-2.

2-port RC network.

zero to infinity and 3 nonzero finite values of C are indicated as shown in Fig. 2-3.

Fig. 2-3.

In general, consider that the value of a parameter can vary from zero to infinity and this range of values can be divided into a number of subdivisions, each of which shall be called the j-th deviation of the parameter value, where $j = 1, 2, ---$. For example, the value of C (between 0 to ∞) is divided into four subdivisons, that is, the 1-st deviation is $0 \leq C < 0.5$, the 2-nd deviation is $0.5 \leq C < 1.2$ and similarly, $1.2 \leq C < 1.5$ and $1.5 \leq C$ represent, respectively, the 3-rd and 4-th deviation.

The normalized $|T12|$ is given by

$$\frac{|T12|_{ji}}{|T12|_{0i}} = \frac{\sqrt{1 + w^2}}{\sqrt{1 + (wC)^2}} \tag{2-3}$$

The values of the normalized $|T12|$ corresponding to the 1-st deviation through the 4-th deviation are shown in Fig. 2-4 according to a set of 3 test frequencies. The values of the normalized $|T12|$ corresponding to the j-th deviation where $j = 1,2,3,4$ are best seen by a coordinate plane whose ordinate represents a frequency axis and abscissa represents a normalized $|T12|$ axis as shown in Fig. 2-5.

Let a "region-j", designated by R-j, represent an area on the frequency-normalized $|T12|$ coordinate plane which corresponds to the j-th deviation of an element. For example, R-1 represents the area to the right of line A-0 (Fig. 2-5) on the frequency-normalized $|T12|$ coordinate plane and corresponds to the 1-st deviation of C. R-2 represents an area between line B-0 and line A-0, including line A-0, on the frequency-normalized $|T12|$ coordinate plane and corresponds to the 2-nd deviation of C as shown in the figure.

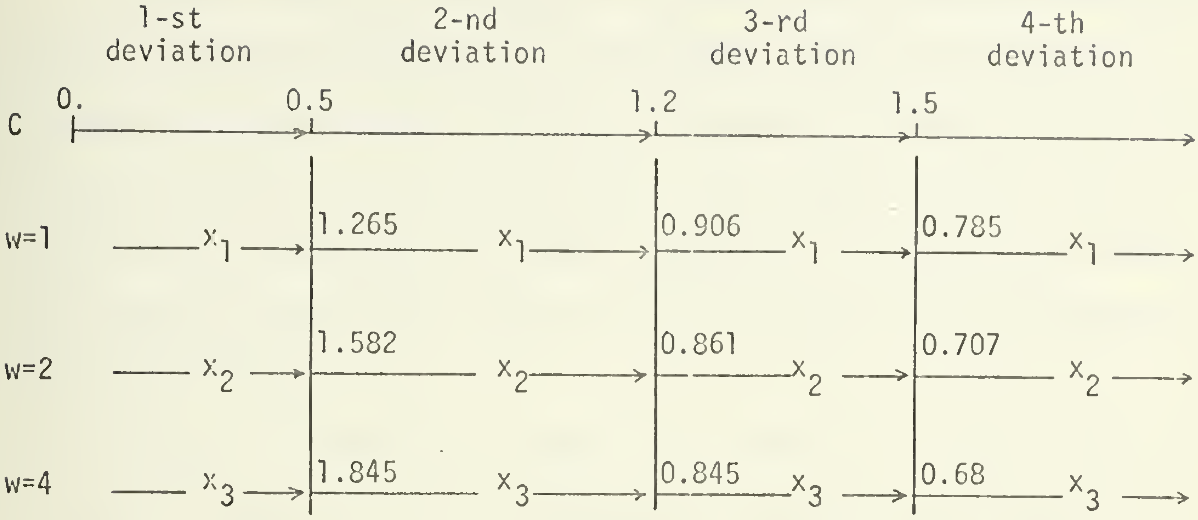


Fig. 2-4.

The normalized |T12| corresponding to the j-th deviation.

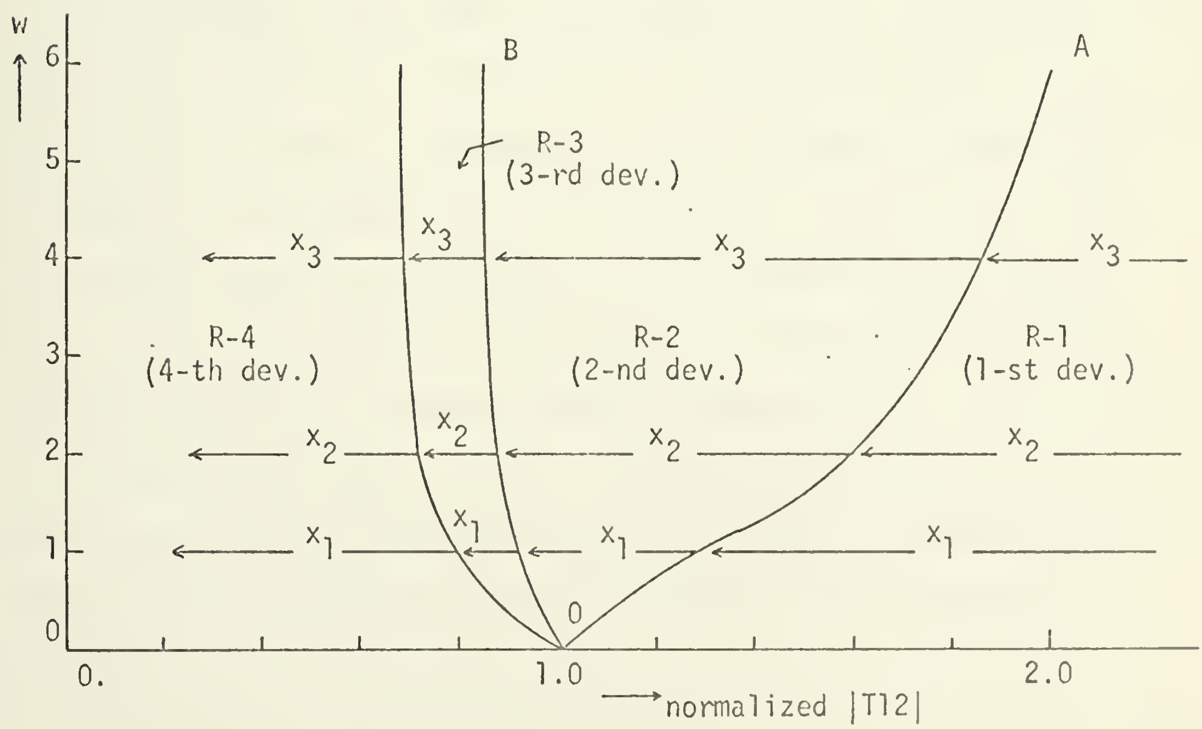


Fig. 2-5.

The frequency-normalized |T12| coordinate plane.

A "normal region" is defined as a region on the frequency-normalized $|T12|$ coordinate plane where a corresponding element deviation is in a predefined normal range of deviation. The region outside of this normal region is defined as a "faulty region". For example, if the 2-nd deviation is a predefined normal range of deviation, R-2 is a normal region. The regions outside of R-2, that is, R-1, R-3 and R-4 are considered to be faulty regions.

Let x_i be a variable in a region R-j of domain x. If the value of x_i is in a normal region, the corresponding element is considered to be normal. For example, let R-2 be a normal region. If the values of x_i where i = 1,2,3 is in R-2, the element C is considered to be normal. Otherwise the element with the values represented by x_i is considered to be faulty.

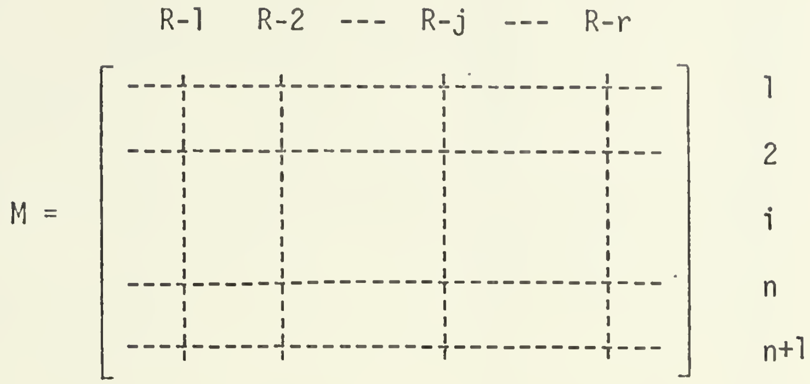
Let a "boundary point value", abbreviated by B.P.V., represent a value of the normalized $|T12|$ which lies between two regions. The boundary point values of a region may or may not belong to that region. For example, the boundary point values between R-1 and R-2 lie on line A-0 and these values do not belong to R-1 but belong to R-2 as shown in Fig. 2-5. The 3 boundary point values corresponding to x_1, x_2 and x_3 in R-1 are 1.265 , 1.582 and 1.845 and belong to R-2.

A "fault identification matrix", designated by M, is defined as a matrix whose number of columns represent the number of regions and the number of rows represent the number of components of $\overline{X}$ as shown in Fig. 2-6.

A vector " $\overline{Z}$ " is defined as

$$\overline{Z}' = \overline{X}'M \qquad (2\text{-}4)$$

(No. of regions = No. of columns)



(No. of $\overline{X}$ components = No. of rows)

Fig. 2-6.

Fault identification matrix.

A method for the construction of M and the generation of $\overline{Z}$ in the n-dimensional domain x with r-regions is presented as follows. The r-regions R-1, R-2, -----, R-j, -----, R-r and p boundary point values b_1, b_2 ----- , b_p , assigned by positive numbers, are defined in Fig. 2-7.

Corresponding to the boundary point values, the r-regions can be arranged with respect to the vector component x_i as shown in Table 2-1. Let the regions, arranged as shown in Table 2-1, be called the "identification regions".

A fault identification matrix, M, will be constructed corresponding to the defined identification regions. For every B.P.V. associated with each vector component, x_i , a sub-fault identification matrix is formed. These sub-fault identification matrices, designated by m_1, m_2 ---- , have the same dimension as M.

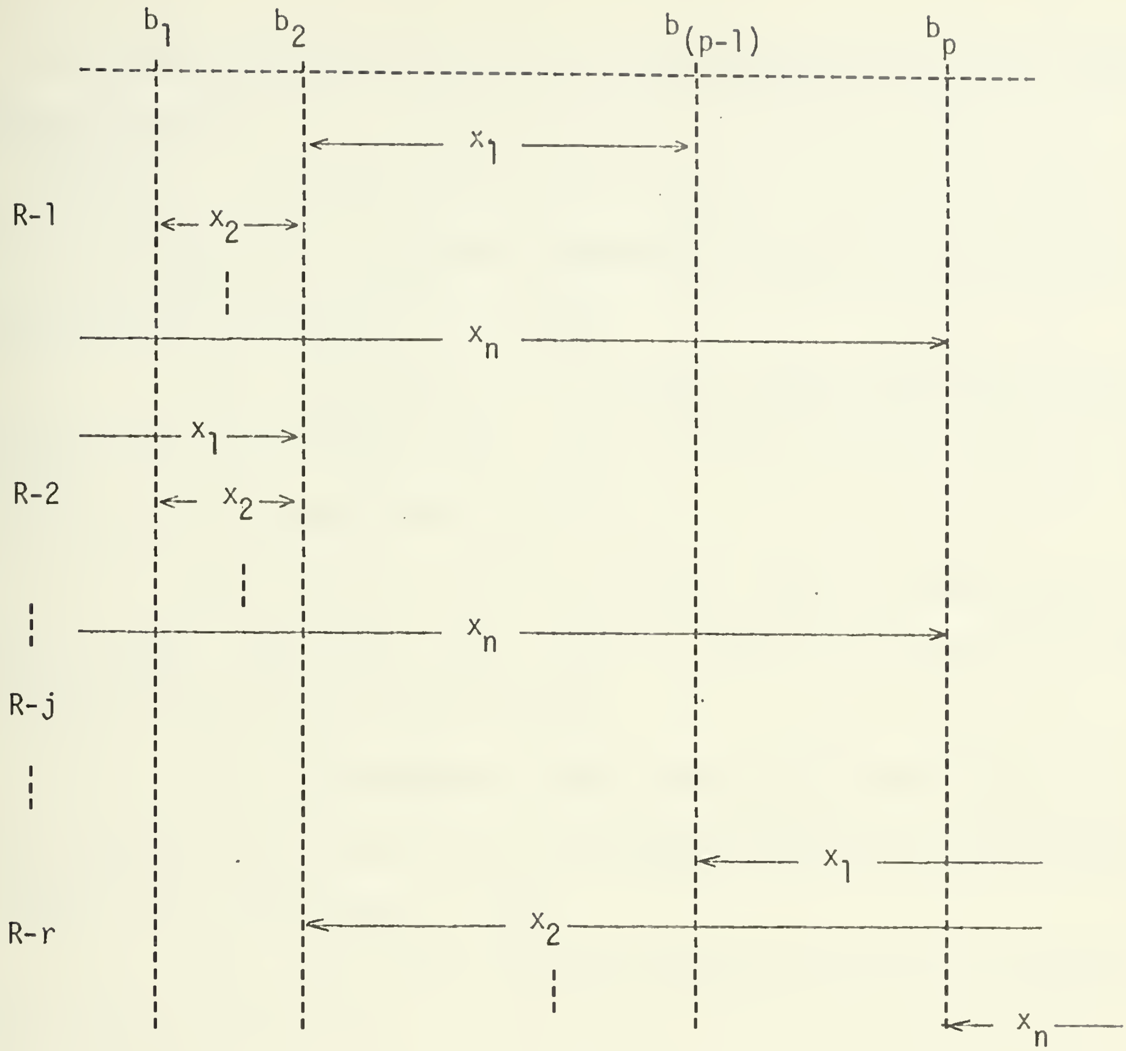


Fig. 2-7.

n-dimensional domain x with r-regions

	R-1	R-2	--- R-j ---	R-r
x_1	$b_2 < x_1 < b_{(p-1)}$	$x_1 < b_2$		$b_{(p-1)} < x_1$
x_2	$b_1 < x_2 < b_2$	$b_1 < x_2 < b_2$		$b_2 < x_2$
⋮				
x_i				
⋮				
x_n	$x_n < b_p$	$x_n < b_p$		$b_p < x_n$

Table 2-1.

Identification regions.

The following rules are given for the construction of a fault identification matrix.

Rule 1:

To construct a sub-fault identification matrix for a particular x_i, the following procedures are used.

(a). If the value of x_i in R-j is greater than the selected B.P.V., that is associated with x_i, put +1 in the i-th row of j-th column of the sub-fault identification matrix.

(b). If the value of x_i in R-j is less than the selected B.P.V., that is associated with x_i, put -1 in the i-th row of j-th column of the sub-fault identification matrix.

(c). To generate the entry of the j-th column of the last row, multiply the selected B.P.V. by the entry value of the j-th column of the i-th row and change its sign.

(d). All entries other than those in the i-th row and the last row are set to zero.

Rule 2:

The fault identification matrix, M, is constructed as a matrix sum of all sub-fault identification matrices.

Using rules 1 and 2, the sub-fault identification matrices and M for the identification regions in Table 2-1 are constructed as follows. With respect to x_1, the sub-fault identification matrices are:

for B.P.V. of $b_{(p-1)}$,

$$m_1 = \begin{array}{c} \begin{array}{ccccccc} \text{R-1} & \text{R-2} & --- & \text{R-j} & --- & \text{R-r} & \end{array} \\ \left[\begin{array}{cccc} -1. & -1. & & +1. \\ 0. & 0. & & 0. \\ & & & \\ 0. & 0. & & 0. \\ +b_{(p-1)} & +b_{(p-1)} & & -b_{(p-1)} \end{array}\right] \begin{array}{c} 1 \\ 2 \\ i \\ n \\ n+1 \end{array} \end{array}$$

and for B.P.V. of b_2,

$$m_2 = \begin{array}{c} \begin{array}{ccccccc} \text{R-1} & \text{R-2} & --- & \text{R-j} & --- & \text{R-r} & \end{array} \\ \left[\begin{array}{cccc} +1. & -1. & & +1. \\ 0. & 0. & & 0. \\ & & & \\ 0. & 0. & & 0. \\ -b_2 & +b_2 & & -b_2 \end{array}\right] \begin{array}{c} 1 \\ 2 \\ i \\ n \\ n+1 \end{array} \end{array}$$

With respect to x_2, the sub-fault identification matrices are:

for B.P.V. of b_2,

$$m_3 = \begin{array}{c} \begin{array}{ccccccc} \text{R-1} & \text{R-2} & --- & \text{R-j} & --- & \text{R-r} & \end{array} \\ \left[\begin{array}{cccc} 0. & 0. & & 0. \\ -1. & -1. & & +1. \\ & & & \\ 0. & 0. & & 0. \\ +b_2 & +b_2 & & -b_2 \end{array}\right] \begin{array}{c} 1 \\ 2 \\ i \\ n \\ n+1 \end{array} \end{array}$$

and for B.P.V. of b_1,

$$
\begin{array}{cccccccc}
 & & R\text{-}1 & R\text{-}2 & --- & R\text{-}j & --- & R\text{-}r & \\
m_4 & = & \left[\begin{array}{c} 0. \\ +1. \\ \\ 0. \\ -b_1 \end{array}\right. & \begin{array}{c} 0. \\ +1. \\ \\ 0. \\ -b_1 \end{array} & & & & \left.\begin{array}{c} 0. \\ +1. \\ \\ 0. \\ -b_1 \end{array}\right] & \begin{array}{c} 1 \\ 2 \\ i \\ n \\ n+1 \end{array}
\end{array}
$$

Finally, with respect to x_n, the sub-fault identification matrix for B.P.V. of b_p is

$$
\begin{array}{cccccccc}
 & & R\text{-}1 & R\text{-}2 & --- & R\text{-}j & --- & R\text{-}r & \\
m_f & = & \left[\begin{array}{c} 0. \\ 0. \\ \\ -1. \\ +b_p \end{array}\right. & \begin{array}{c} 0. \\ 0. \\ \\ -1. \\ +b_p \end{array} & & & & \left.\begin{array}{c} 0. \\ 0. \\ \\ +1. \\ -b_p \end{array}\right] & \begin{array}{c} 1 \\ 2 \\ i \\ n \\ n+1 \end{array}
\end{array}
$$

where m_f means the last sub-fault identification matrix.

The resulting M is given by

$$M = m_1 + m_2 + m_3 + m_4 + \text{------} + m_f$$

$$
\begin{array}{cccccccc}
 & & R\text{-}1 & R\text{-}2 & --- & R\text{-}j & --- & R\text{-}r & \\
M & = & \left[\begin{array}{c} 0. \\ 0. \\ \\ -1. \\ A_1 \end{array}\right. & \begin{array}{c} -2. \\ 0. \\ \\ -1. \\ A_2 \end{array} & & & & \left.\begin{array}{c} +2. \\ +2. \\ \\ +1. \\ A_r \end{array}\right] & \begin{array}{c} 1 \\ 2 \\ i \\ n \\ n+1 \end{array}
\end{array}
$$

where $A_1 = b_{(p-1)} - b_1 + --- + b_p$, $A_2 = b_{(p-1)} + 2b_2 - b_1 + --- + b_p$

and $A_r = - b_{(p-1)} - 2b_2 - b_1 + --- - b_p$.

Next, the application of M for the generation of $\overline{Z}$ is discussed. Let the normalized values of $|T12|$ of a system be $x_1, x_2, ----- , x_n$. $\overline{X}$ is in the form of

$$\overline{X} = [x_1, x_2, --- , x_i, --- , x_n, 1.]$$

$\overline{Z}'$ is generated as follows.

$$\begin{aligned} \overline{Z}' &= \overline{X}'M = [x_1, x_2, -------- ; x_n, 1.] M \\ &= [-x_n+A_1 , -2x_1+ --- -x_n+A_2 , ------- , 2x_1+2x_2 -- +x_n+A_r] \\ &= [z_1 , z_2 , --- , z_j , ----- , z_r] \end{aligned}$$

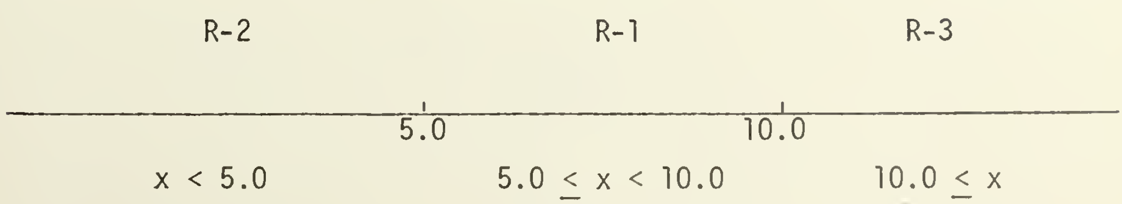
$\overline{Z}$ has the same number of components as the number of regions and z_j serves as an indicator of the region in which the system is operating as given by the following rule.

Rule 3:

If a system is operating in R-j, the component z_j of $\overline{Z}$ is the algebraically largest component in $\overline{Z}$.

The construction of M and the generation of $\overline{Z}$ are illustrated in the following examples.

Example 2.1. Construct M and generate $\overline{Z}$ in the following one dimensional domain x with three regions.



Corresponding to the given boundary point values, the identification regions are as follows.

	R-1	R-2	R-3
x	$5.0 \leq x < 10.0$	$x < 5.0$	$10.0 \leq x$

Using rules 1 and 2, the sub-fault identification matrices and M for the identification regions are constructed.

The sub-fault identification matrix for B.P.V. of 5.0 is

$$m_1 = \begin{array}{ccc} \text{R-1} & \text{R-2} & \text{R-3} \end{array}$$
$$m_1 = \begin{bmatrix} +1. & -1. & +1. \\ -5.0 & +5.0 & -5.0 \end{bmatrix}$$

and the sub-fault identification matrix for B.P.V. of 10.0 is

$$\begin{array}{ccc} \text{R-1} & \text{R-2} & \text{R-3} \end{array}$$
$$m_2 = \begin{bmatrix} -1. & -1. & +1. \\ +10.0 & +10.0 & -10.0 \end{bmatrix}$$

The resulting M is given by

$$\begin{array}{ccc} \text{R-1} & \text{R-2} & \text{R-3} \end{array}$$
$$M = m_1 + m_2 = \begin{bmatrix} 0. & -2. & 2. \\ 5.0 & 15.0 & -15.0 \end{bmatrix}$$

Suppose that the measured value of x is 13.0. $\overline{X}$ is in the form of

$$\overline{X}' = [\ x\ ,\ 1.\ ]$$
$$[\ 13.0 \quad 1.\ ]$$

Thus, $\bar{Z}'$ is obtained

$$\bar{Z}' = \bar{X}'M = [\ 13.0 \quad 1.\ ] \begin{bmatrix} 0. & -2. & 2. \\ 5.0 & 15.0 & -15.0 \end{bmatrix}$$

$$= [\ 5. \quad -11. \quad 11.\ ]$$

$$[\ z_1\ , \quad z_2\ , \quad z_3\ ]$$

in which z_3 is the algebraically largest component. According to rule 3, the system is operating in R-3. The measured value of x, indeed, belongs to R-3.

If the measured value of x is 6.0, then

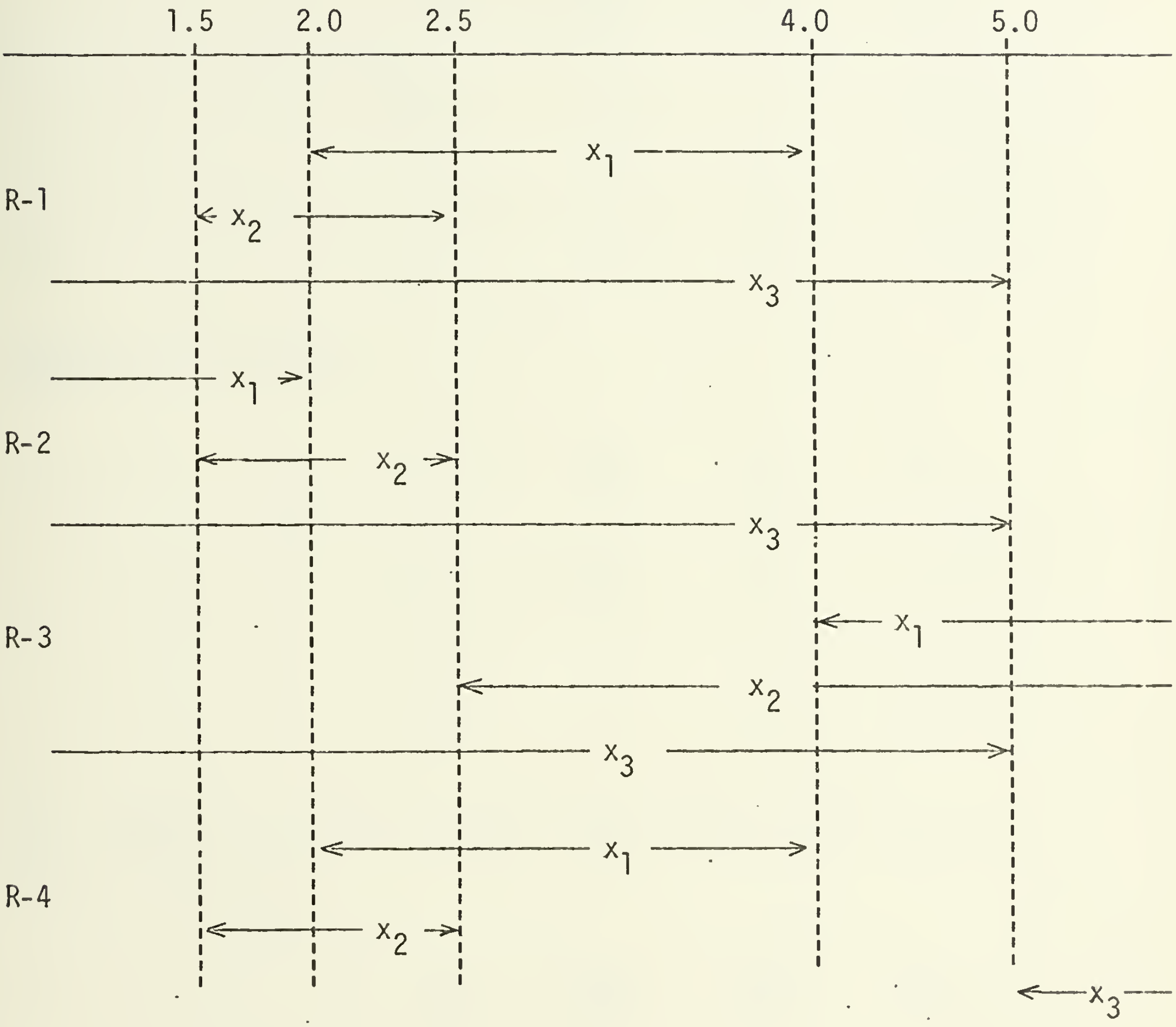
$$\bar{Z}' = \bar{X}'M = [\ 6.0 \quad 1.\ ] \begin{bmatrix} 1. & -2. & 2. \\ 5.0 & 15.0 & -15.0 \end{bmatrix}$$

$$= [\ 5. \quad 3. \quad 3.\ ]$$

$$= [\ z_1\ , \quad z_2\ , \quad z_3\ ]$$

The fact that $z_1 = 5$, the largest of all the entries in $\bar{Z}'$, indicates that the system is operating in R-1.

Example 2.2. Construct M and generate $\overline{Z}$ in the following three dimensional domain x with four regions.



The boundary point values are 1.5 , 2.0 , 2.5 , 4.0 and 5.0 . The identification regions are defined as follows.

	R-1	R-2	R-3	R-4
x_1	$2.0 < x_1 < 4.0$	$x_1 < 2.0$	$4.0 < x_1$	$2.0 < x_1 < 4.0$
x_2	$1.5 < x_2 < 2.5$	$1.5 < x_2 < 2.5$	$2.5 < x_2$	$1.5 < x_2 < 2.5$
	$x_3 < 5.0$	$x_3 < 5.0$	$x_3 < 5.0$	$5.0 < x_3$

With respect to x_1, the sub-fault identification matrices are:

for B.P.V. of 4.0,

$$
\begin{array}{c@{\;}c@{\;}c}
 & \begin{array}{cccc} \text{R-1} & \text{R-2} & \text{R-3} & \text{R-4} \end{array} & \\
m_1 = & \begin{bmatrix} -1. & -1. & 1. & -1. \\ 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. \\ 4. & 4. & -4. & 4. \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array}
\end{array}
$$

and for B.P.V. of 2.0,

$$
\begin{array}{c@{\;}c@{\;}c}
 & \begin{array}{cccc} \text{R-1} & \text{R-2} & \text{R-3} & \text{R-4} \end{array} & \\
m_2 = & \begin{bmatrix} 1. & -1. & 1. & 1. \\ 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. \\ -2. & 2. & -2. & -2. \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array}
\end{array}
$$

With respect to x_2, the sub-fault identification matrices are:

for B.P.V. of 2.5,

$$
\begin{array}{c@{\;}c@{\;}c}
 & \begin{array}{cccc} \text{R-1} & \text{R-2} & \text{R-3} & \text{R-4} \end{array} & \\
m_3 = & \begin{bmatrix} 0. & 0. & 0. & 0. \\ -1. & -1. & 1. & -1. \\ 0. & 0. & 0. & 0. \\ 2.5 & 2.5 & -2.5 & 2.5 \end{bmatrix} & \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array}
\end{array}
$$

and for B.P.V. of 1.5,

$$m_4 = \begin{array}{c} \\ \\ \\ \\ \\ \end{array}\begin{array}{cccc} R\text{-}1 & R\text{-}2 & R\text{-}3 & R\text{-}4 \end{array}$$

$$m_4 = \begin{bmatrix} 0. & 0. & 0. & 0. \\ 1. & 1. & 1. & 1. \\ 0. & 0. & 0. & 0. \\ -1.5 & -1.5 & -1.5 & -1.5 \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array}$$

With respect to x_3, the sub-fault identification matrix for B.P.V. of 5.0 is

$$\begin{array}{cccc} R\text{-}1 & R\text{-}2 & R\text{-}3 & R\text{-}4 \end{array}$$

$$m_5 = \begin{bmatrix} 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. \\ -1. & -1. & -1. & 1. \\ 5. & 5. & 5. & -5. \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array}$$

The resulting M is given by

$$\begin{array}{cccc} R\text{-}1 & R\text{-}2 & R\text{-}3 & R\text{-}4 \end{array}$$

$$M = m_1 + m_2 + m_3 + m_4 + m_5 = \begin{bmatrix} 0. & -2. & 2. & 0. \\ 0. & 0. & 2. & 0. \\ -1. & -1. & -1. & 1. \\ 8. & 12. & -5. & -2. \end{bmatrix} \begin{array}{c} 1 \\ 2 \\ 3 \\ 4 \end{array}$$

If the measured components of $\overline{X}$ are $x_1 = 3.0$, $x_2 = 2.0$ and $x_3 = 3.0$, $\overline{X}'$ becomes

$$\overline{X}' = [\ 3. \quad 2. \quad 3. \quad 1.\ ]$$

$$\overline{Z}' = \overline{X}'M = [\ 3. \quad 2. \quad 3. \quad 1.\ ]\ M = [\ 5. \quad 3. \quad 2. \quad 1.\ ]$$
$$= [\ z_1\ ,\ z_2\ ,\ z_3\ ,\ z_4\ ]$$

The component z_1 is the albebraically largest component. According to rule 3, the system is operating in R-1. Similarly, if the measured components of $\overline{X}$ are $x_1 = 3.0$, $x_2 = 2.0$ and $x_3 = 6.0$, $\overline{Z}$ is given by

$$\overline{Z}' = \overline{X}'M = [\ 3. \quad 2. \quad 6. \quad 1.\ ]\ M = [\ 2. \quad 0. \quad -1. \quad 4.\ ]$$

$$= [\ z_1\ ,\ z_2\ ,\ z_3\ ,\ z_4\ ]$$

The component z_4 indicates that the system is operating in R-4.

III. THE PROPOSED METHOD

A. PURPOSE

The purpose of the proposed method is to investigate a feasible method to determine whether fault detection and isolation can be accomplished by measuring only the magnitude of the system transfer frunction. In this method, the least number of test frequencies and test points, such as the normal input and output terminals of the system, will be used.

B. BASIS FOR THE PROPOSED METHOD

Consider again the 2-port network shown in Fig. 2-1. The open circuit impedance functions are represented by the equations of the voltages as linear functions of the currents in matrix form as follows.

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{3-1}$$

The network of the type being considered can be externally characterized by a transfer function in terms of open circuit impedances. It is easily found that the forward voltage ratio transfer function, T12, and the reverse voltage ratio transfer function, T21, (defined as the ratio of the input voltage to the output voltage with the input current set to zero) are

$$T12 = \frac{z_{21}}{z_{11}} \tag{3-2}$$

$$T21 = \frac{z_{12}}{z_{22}} \tag{3-3}$$

In general, a transfer function can be expressed as a rational function of the complex frequency, s, and a network element, E, as follows.

$$T(s,E) = \frac{K \prod_{i=1}^{m} (s + z_i)}{\prod_{j=1}^{n} (s + p_j)} \tag{3-4}$$

where zero, z_i, and pole, p_j, and K are functions of E and m and n are the number of zeroes and poles respectively.

Taking the logarithm of Eq. (3-4), the following equation is obtained

$$\ln T(s,E) = \ln K + \sum_{i=1}^{m} \ln(s + z_i) - \sum_{j=1}^{n} \ln(s + p_j) \tag{3-5}$$

And taking the derivative of Eq. (3-5), the following equation is obtained.

$$d(\ln T(s,E)) = \frac{d(T(s,E))}{T(s,E)}$$

$$= \left[\frac{1}{K}\frac{dK}{dE} + \sum_{i=1}^{m} \frac{1}{s+z_i}\frac{dz_i}{dE} - \sum_{j=1}^{n} \frac{1}{s+p_j}\frac{dp_j}{dE}\right] dE \tag{3-6}$$

A "transfer function sensitivity" is represented by Eq. (3-6). The transfer function sensitivity is closely related to pole and zero sensitivities where "$\frac{dp_j}{dE}$" and "$\frac{dz_i}{dE}$" are defined as pole sensitivity and zero sensitivity respectively. In other words, the variation of T(s,E) may take the form of a change in location of a pole and/or a zero of T(s,E).

From Eq. (3-4) and Eq. (3-6), it can be seen that a change in any one of the pole-zero configurations will cause a change in one or possibly both of the voltage ratio transfer functions. Since T12(s,E) and T21(s,E) depend on the value of E, it is not hard to consider how a change of an internal element is related to a change of an external voltage ratio transfer function.

This is the basic philosophy of the proposed method for fault identification.

C. PROPOSED TEST PROCEDURE

A fundamental fault testing procedure for the proposed method is given as follows.

Step (1). Partition the system.

Step (2). Generate a symbolic system function.

Step (3). Select a set of test frequencies.

Step (4). Simulate a fault.

Step (5). Determine the fault identification regions.

Step (6). Construct the fault identification matrix.

Step (7). Generate $\overline{X}$.

Step (8). Generate $\overline{Z}$.

Step (9). Identify the fault.

(a). Single element.

(b). Combined element.

Step (2), step (3) and part of step (4) have been studied and a computer program of these steps for the passive linear network without mutual inductance was presented by J. D. Courville in Ref. [2]. The detailed discussion of these steps will be omitted. The other steps are discussed in detail in the next chapter illustrative examples.

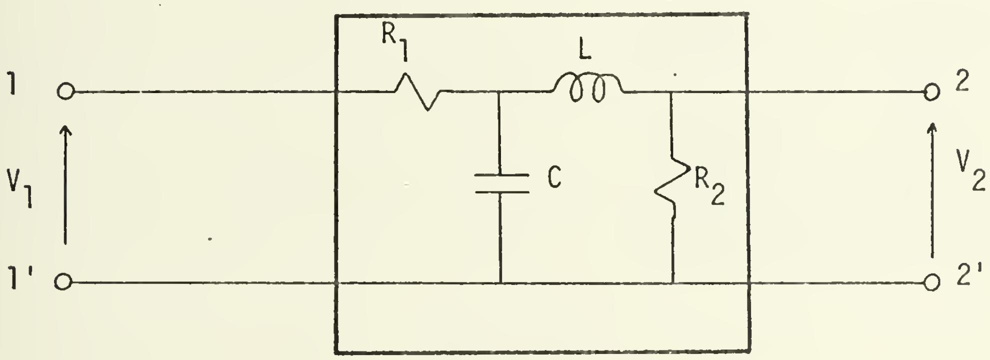
IV. NETWORK FAULT IDENTIFICATION

A. NETWORK CONFIGURATIONS AND TRANSFER FUNCTIONS

As illustrated in the foregoing discussions, there is a certain relationship between the transfer function and a network element deviation.

To illustrate the proposed method, two examples for passive network configurations are presented.

Example 4.1:



$1/Ea1 = R_1 = 2$ ohms

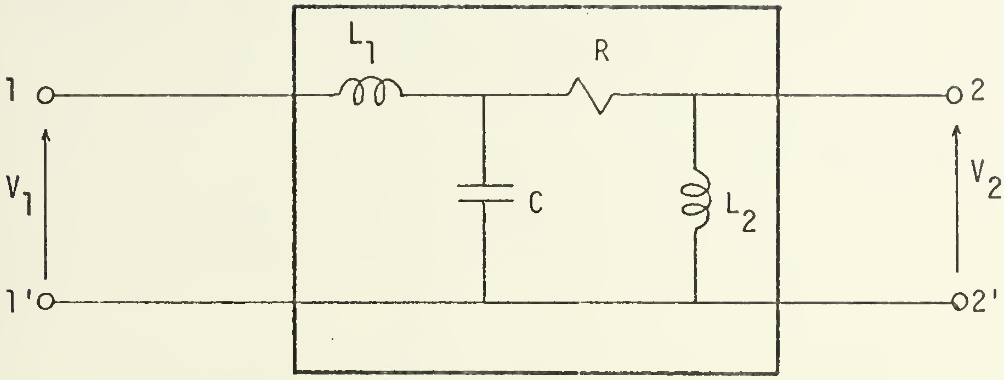
$1/Ea2 = L = 2$ henry

$Ea3 = C = 3$ farads

$1/Ea4 = R_2 = 4$ ohms

Fig. 4-1(a).

Example 4.2:



$1/Eb1 = L_1 = 1$ henry

$1/Eb2 = R = 1$ ohm

$Eb3 = C = 1$ farad

$1/Eb4 = L_2 = 1$ henry

Fig. 4-1(b).

For example 4.1, the transfer function is

$$T12 = \frac{R_2}{R_1LCs^2 + (R_1R_2C+L)s + R_1 + R_2}$$

$$= \frac{1}{3s^2 + 6.5s + 1.5}$$

$$= \frac{K_1}{(s+0.262)(s+1.90)} \qquad (4\text{-}1a)$$

where K_1 is 1/3 .

For example 4.2, the transfer function is

$$T12 = \frac{L_2 s}{L_1 L_2 C s^3 + R L_1 C s^2 + (L_1 + L_2)s + R}$$

$$= \frac{s}{s^3 + s^2 + 2s + 1}$$

$$= \frac{K_2 s}{(s+0.57)(s^2+0.43s+1.7623)} \qquad (4\text{-}1b)$$

where K_2 is 1 .

The network semilogarithmic plots for the magnitude characteristic of the transfer function are shown in Fig. 4-2a for Eq. 4-1a and Fig. 4-2b for Eq. 4-1b.

B. NECESSARY DATA

All necessary data for the proposed method are based on a set of chosen test frequencies.

A "fault simulation curve" is defined as a response curve of the normalized $|T12|$ variations due to the simulated deviations of an element with respect to a chosen test frequency. The fault simulated data for $|T12|$ can be obtained from the computer program in Ref. [2]. The fault simulated data for $|T12|$ and the normalized $|T12|$ are tabulated in Tables 4-1a and 4-1b for Eq. 4-1a and Eq. 4-1b respectively.

The fault simulation curves are drawn in Graph 4-1a-1 thru Graph 4-1a-3 for example 4.1 and Graph 4-1b-1 thru Graph 4-1b-3 for example 4.2.

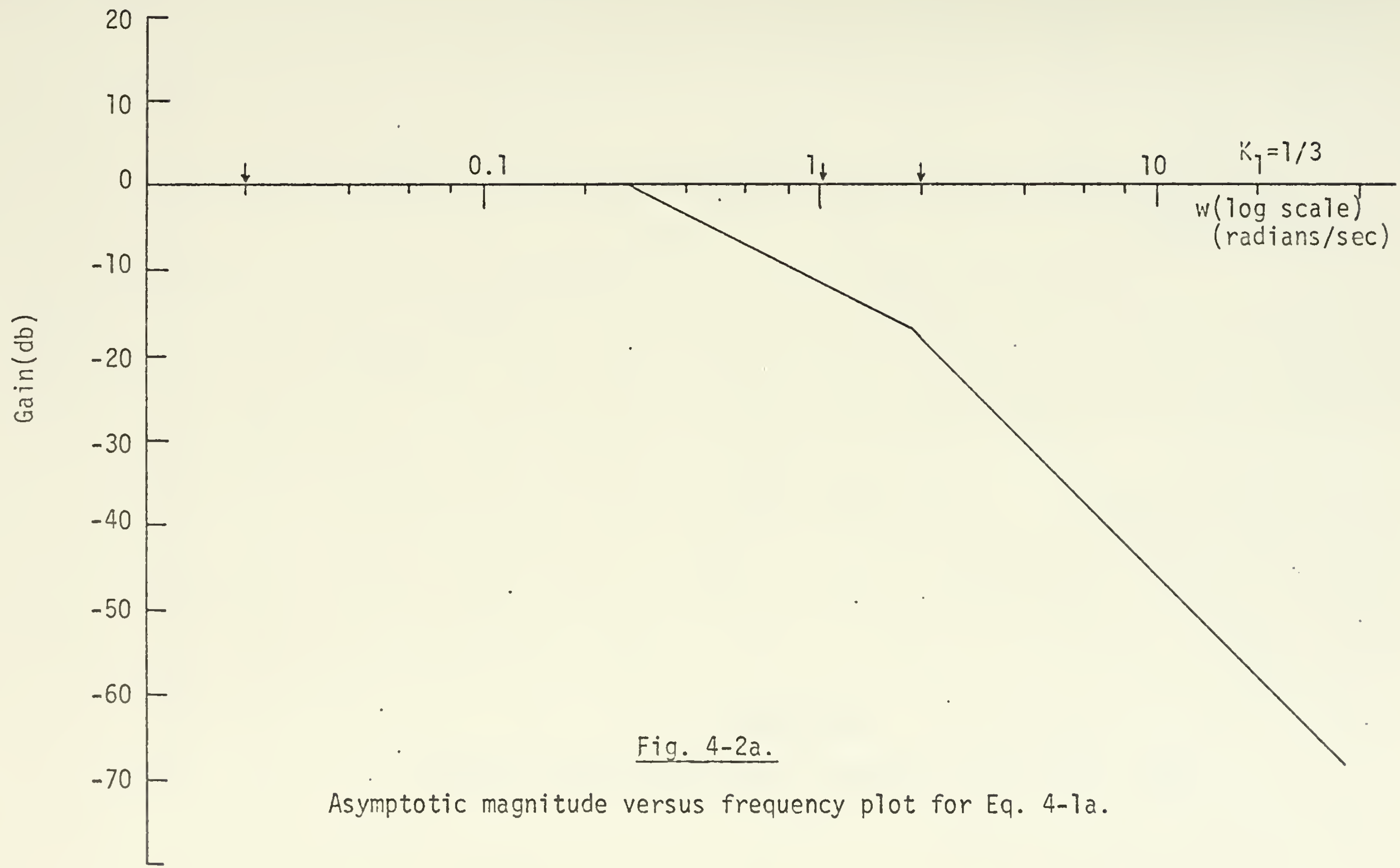


Fig. 4-2a.

Asymptotic magnitude versus frequency plot for Eq. 4-1a.

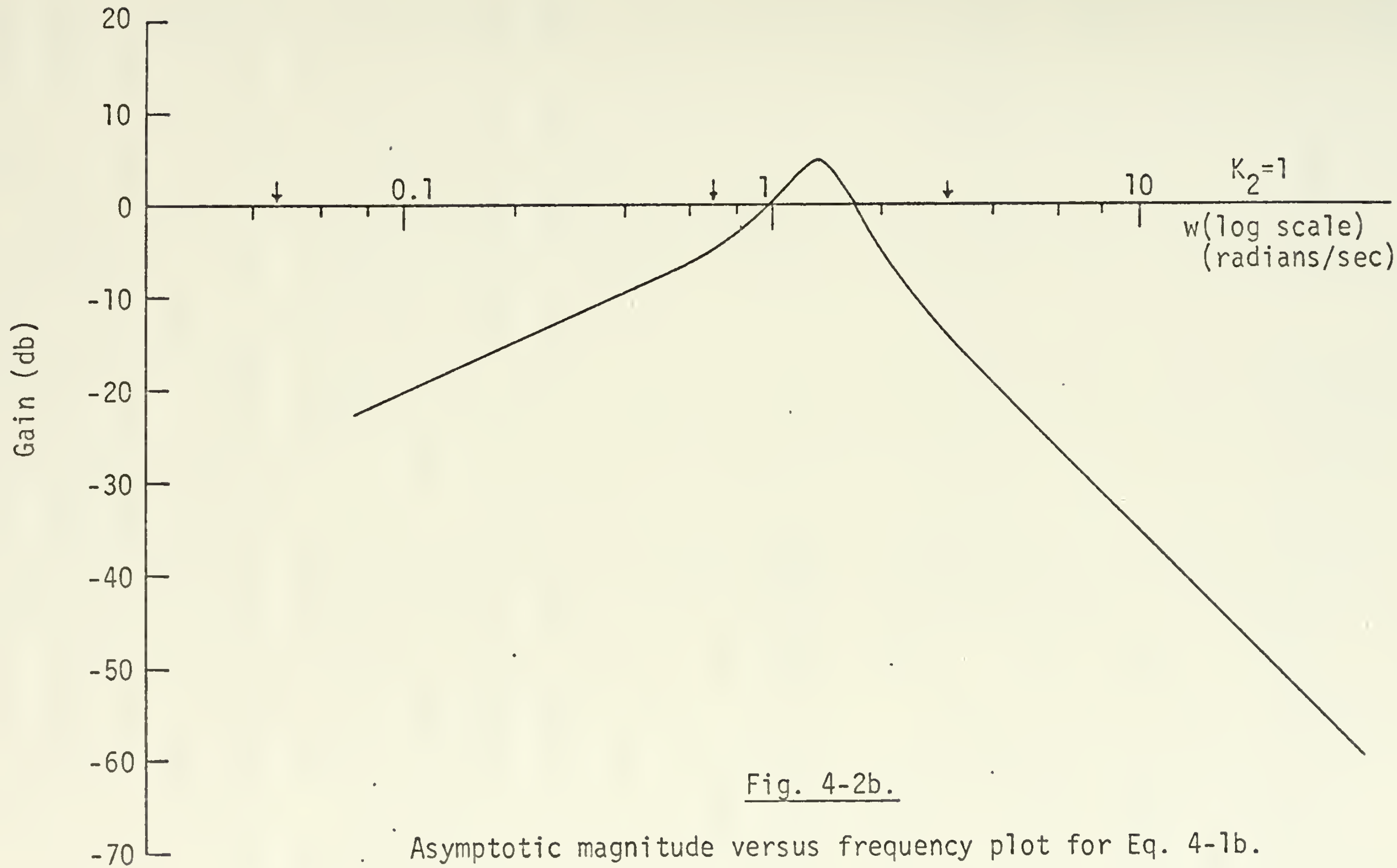


Fig. 4-2b.

Asymptotic magnitude versus frequency plot for Eq. 4-1b.

C. DETERMINATION OF FAULT IDENTIFICATION REGIONS

The proper determination of the identification regions is the most laborious part of the proposed method.

For example 4.1, a set of 3 test frequencies is chosen as follows.

$$w_1 = 2.00 \quad \text{radians/sec}$$

$$w_2 = 1.02 \quad \text{radians/sec}$$

$$w_3 = 0.02 \quad \text{radians/sec}$$

For example 4.2, a set of 3 test frequencies is chosen as follows

$$w_1 = 3.20 \quad \text{radians/sec}$$

$$w_2 = 0.70 \quad \text{radians/sec}$$

$$w_3 = 0.05 \quad \text{radians/sec}$$

For a test frequency, there are eight basic identification regions, four normal regions and four faulty regions, because four elements are contained in the examples. That is, each element has two regions, a normal region and a faulty region. The four normal regions are not the concern of the propsed method. The four faulty regions may be subdivided into many faulty regions to identify a fault. These subdivisions of the faulty regions depend on the transfer function sensitivity. The subdivided faulty regions are called the fault identification regions.

The normal regions for the networks are defined as in Table 4-2a for example 4.1 and Table 4-2b for example 4.2 according to the fault simulation curves. The regions outside of the normal regions are considered to be faulty regions. The fault identification regions are defined as

	DEV (percent)	MAG-T1 (w=2.0)	MAG-T2 (w=1.02)	MAG-T3 (w=0.02)	NOR-T1	NOR-T2	NOR-T3
Ea1	90	0.11247	0.26665	0.79074	1.8795	1.8199	1.1896
	70	0.10092	0.24123	0.77166	1.6865	1.6464	1.1609
	50	0.08928	0.21504	0.74875	1.4920	1.4677	1.1264
	30	0.07756	0.18812	0.72074	1.2961	1.2840	1.0843
	10	0.06576	0.16054	0.68572	1.0990	1.0957	1.0316
	-10	0.05390	0.13235	0.64069	0.9008	0.9033	0.9639
	-30	0.04199	0.10362	0.58067	0.7017	0.7072	0.8736
	-50	0.03003	0.07442	0.49673	0.5018	0.5079	0.7473
	-70	0.01803	0.04485	0.37120	0.3014	0.3061	0.5584
	-90	0.00602	0.01500	0.16370	0.1005	0.1024	0.2463
Ea2	90	0.07451	0.15650	0.66464	1.2452	1.0681	0.9999
	70	0.07267	0.15555	0.66465	1.2144	1.0617	0.9999
	50	0.07024	0.15418	0.66466	1.1737	1.0523	0.9999
	30	0.06699	0.15211	0.66467	1.1195	1.0382	0.9999
	10	0.06260	0.14885	0.66470	1.0461	1.0160	1.0000
	-10	0.05662	0.14347	0.66473	0.9462	0.9792	1.0000
	-30	0.04851	0.13404	0.66477	0.8106	0.9149	1.0001
	-50	0.03774	0.11667	0.66484	0.6306	0.7963	1.0002
	-70	0.02413	0.08439	0.66497	0.4032	0.5760	1.0004
	-90	0.00830	0.03149	0.66482	0.1386	0.2149	1.0002
Ea3	90	0.03131	0.07739	0.65942	0.5232	0.5282	0.9920
	70	0.03502	0.08652	0.66088	0.5853	0.5905	0.9942
	50	0.03974	0.09805	0.66217	0.6641	0.6692	0.9962
	30	0.04591	0.11308	0.66331	0.7673	0.7718	0.9979
	10	0.05435	0.13341	0.66428	0.9082	0.9106	0.9994
	-10	0.06656	0.16238	0.66509	1.1122	1.1082	1.0006
	-30	0.08576	0.20630	0.66574	1.4331	1.4094	1.0015
	-50	0.12017	0.28008	0.66621	2.0081	1.9116	1.0023
	-70	0.19776	0.41447	0.66651	3.3047	2.8288	1.0027
	-90	0.45038	0.61200	0.66665	7.5262	4.1770	1.0029
Ea4	90	0.03991	0.12301	0.51212	0.6669	0.8395	0.7704
	70	0.04336	0.12829	0.53966	0.7246	0.8756	0.8119
	50	0.04733	0.13364	0.57032	0.7910	0.9121	0.8580
	30	0.05188	0.13894	0.60467	0.8670	0.9483	0.9097
	10	0.05704	0.14407	0.64342	0.9532	0.9833	0.9680
	-10	0.06277	0.14886	0.68746	1.0489	1.0160	1.0342
	-30	0.06884	0.15313	0.73795	1.1504	1.0451	1.1102
	-50	0.07478	0.15668	0.79642	1.2497	1.0694	1.1981
	-70	0.07973	0.15932	0.86491	1.3324	1.0874	1.3012
	-90	0.08264	0.16091	0.94624	1.3809	1.0982	1.4235

Table 4-1a.

The magnitudes and the normalized magnitudes of T12 due to each element deviations for Example 4.1.

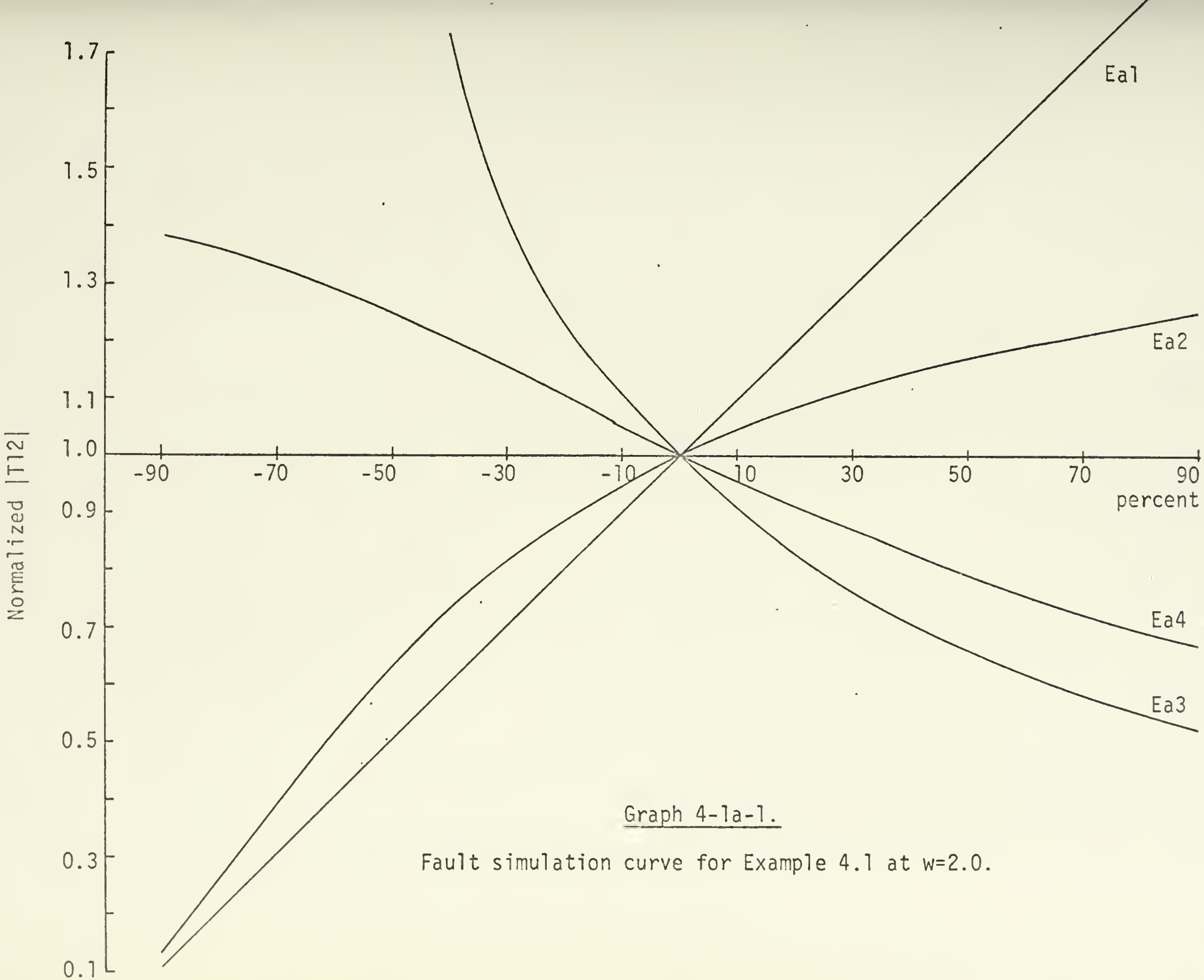
(The nominal magnitudes are 0.05984 at w=2.0 , 0.1465 at w=1.02 and 0.6647 at w=0.02)

	DEV (percent)	MAG-T1 (w=3.2)	MAG-T2 (w=0.7)	MAG-T3 (w=0.05)	NOR-T1	NOR-T2	NOR-T3
Eb1	90	0.24394	0.60490	0.04991	2.1299	1.0142	1.0009
	70	0.21254	0.60589	0.04990	1.8558	1.0158	1.0008
	50	0.18275	0.60623	0.04990	1.5957	1.0164	1.0007
	30	0.15445	0.60512	0.04989	1.3485	1.0146	1.0005
	10	0.12751	0.60085	0.04987	1.1134	1.0074	1.0002
	-10	0.10186	0.58945	0.04985	0.8893	0.9883	0.9997
	-30	0.07739	0.56150	0.04980	0.6757	0.9414	0.9987
	-50	0.05403	0.49499	0.04968	0.4717	0.8299	0.9963
	-70	0.03170	0.35117	0.04925	0.2768	0.5888	0.9877
	-90	0.01034	0.12104	0.04468	0.0903	0.2029	0.8961
Eb2	90	0.11935	0.64187	0.09353	1.0420	1.0762	1.8759
	70	0.11886	0.63708	0.08398	1.0378	1.0681	1.6843
	50	0.11818	0.63043	0.07433	1.0318	1.0570	1.4908
	30	0.11718	0.62085	0.06460	1.0231	1.0409	1.2956
	10	0.11563	0.60646	0.05479	1.0096	1.0168	1.0989
	-10	0.11309	0.58365	0.04492	0.9874	0.9786	0.9008
	-30	0.10852	0.54525	0.03499	0.9475	0.9142	0.7018
	-50	0.09938	0.47653	0.02502	0.8677	0.7990	0.5019
	-70	0.07892	0.34967	0.01503	0.6891	0.5863	0.3014
	-90	0.03330	0.13439	0.00501	0.2908	0.2253	0.1005
Eb3	90	0.05440	0.93146	0.04997	0.4749	1.5617	1.0022
	70	0.06158	0.83950	0.04995	0.5377	1.4075	1.0017
	50	0.07095	0.75730	0.04992	0.6195	1.2697	1.0012
	30	0.08369	0.68570	0.04990	0.7307	1.1497	1.0007
	10	0.10200	0.62398	0.04987	0.8906	1.0462	1.0002
	-10	0.13056	0.57089	0.04985	1.1400	0.9572	0.9998
	-30	0.18130	0.52510	0.04982	1.5830	0.8804	0.9993
	-50	0.29628	0.48544	0.04980	2.5869	0.8139	0.9988
	-70	0.79850	0.45090	0.04877	6.9719	0.7560	0.9782
	-90	1.02460	0.42067	0.04975	8.9460	0.7053	0.9978
Eb4	90	0.10913	0.35980	0.02630	0.9528	0.6032	0.5274
	70	0.11115	0.39472	0.02938	0.9705	0.6618	0.5893
	50	0.11275	0.43707	0.03329	0.9844	0.7328	0.6677
	30	0.11386	0.48950	0.03840	0.9942	0.8207	0.7701
	10	0.11445	0.55602	0.04535	0.9993	0.9322	0.9095
	-10	0.11448	0.64307	0.05537	0.9995	1.0782	1.1105
	-30	0.11395	0.76155	0.07106	0.9949	1.2768	1.4252
	-50	0.11289	0.93135	0.09911	0.9856	1.5615	1.9877
	-70	0.11134	1.19190	0.16324	0.9721	1.9984	3.2740
	-90	0.10935	1.62772	0.43908	0.9548	2.7291	8.8061

Table 4-1b.

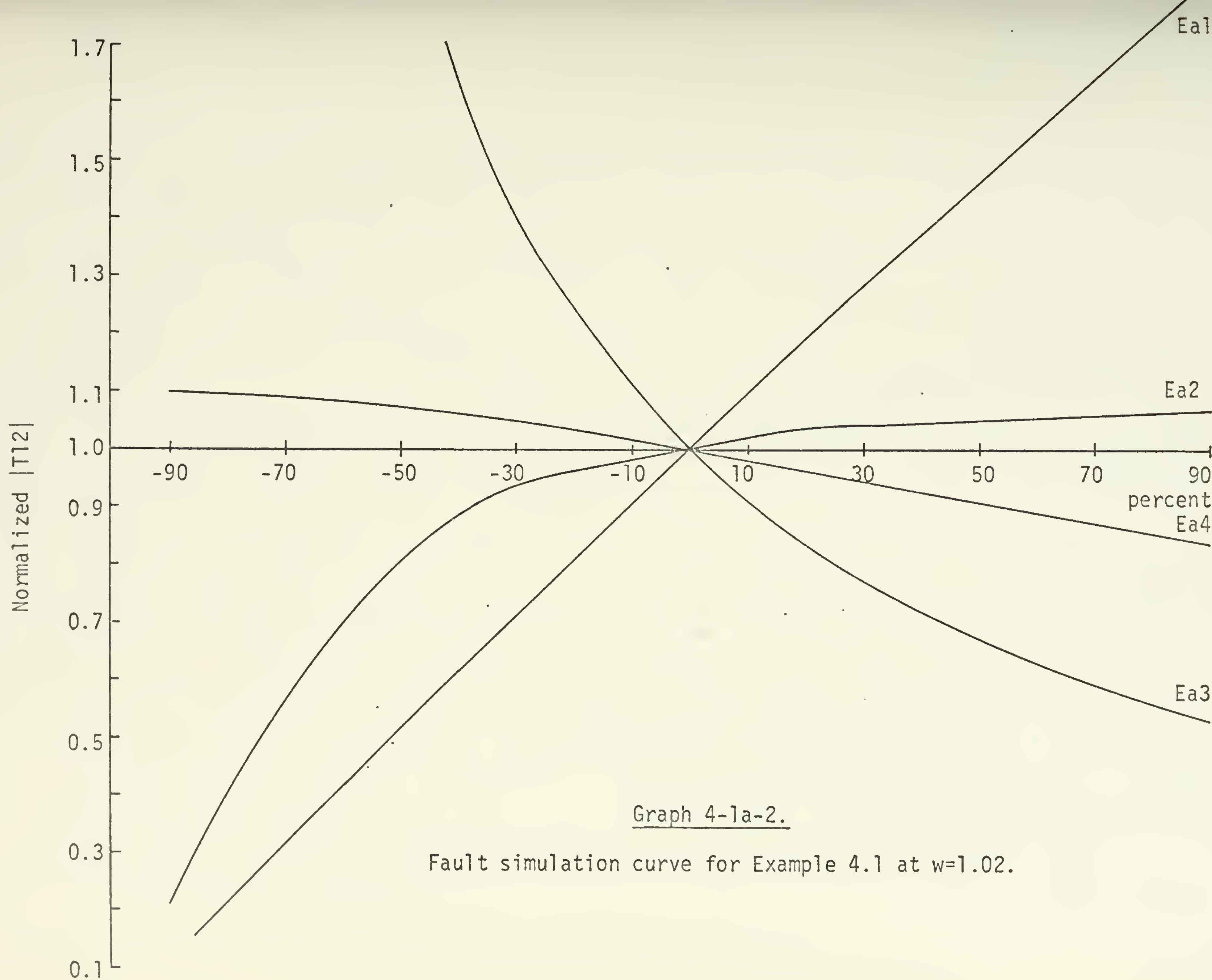
The magnitudes and the normalized magnitudes of T12 due to each element deviations for Example 4.2.

(The nominal magnitudes are 0.11453 at w=3.2 , 0.5964 at w=0.7 and 0.04986 at w=0.05)



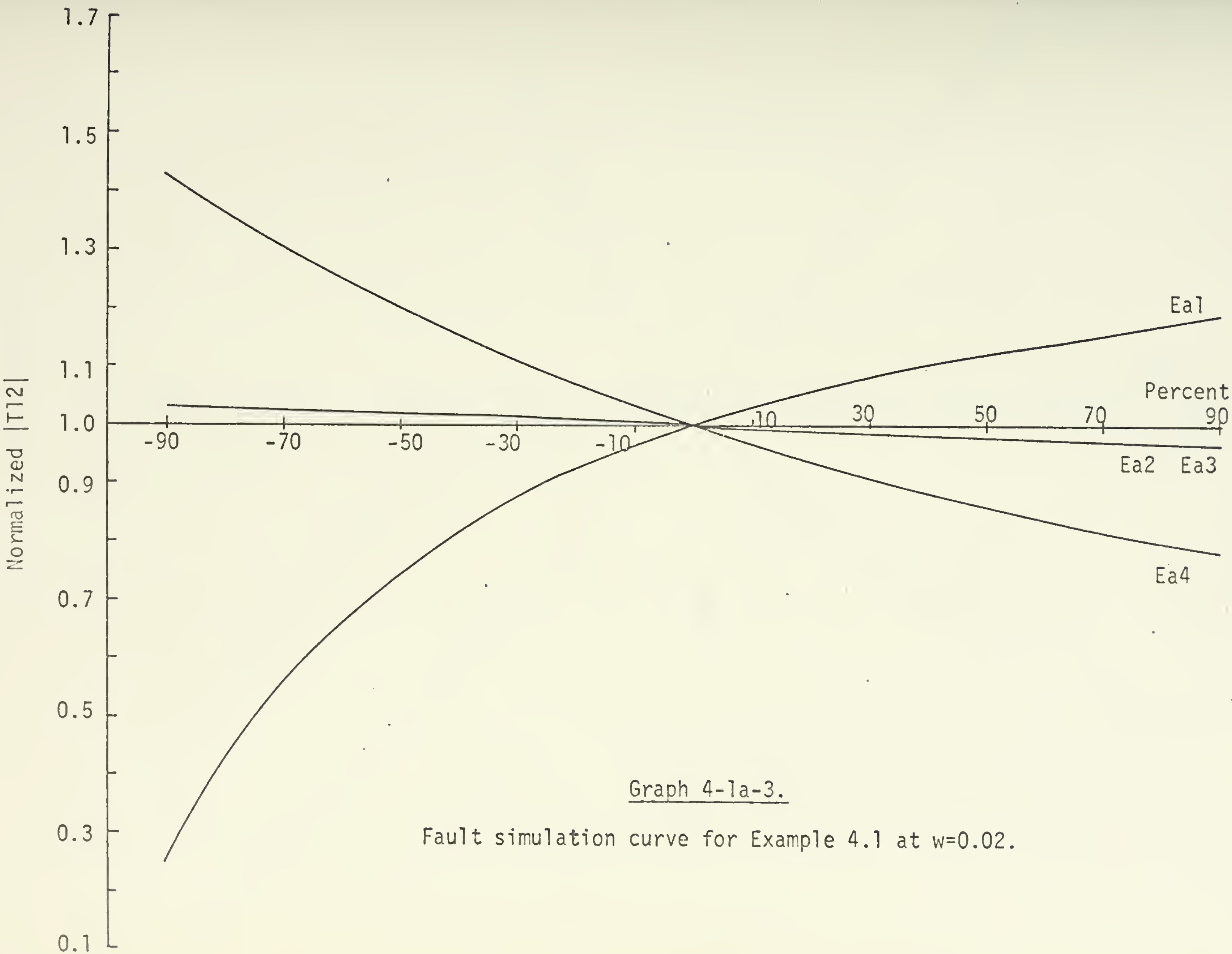
Graph 4-1a-1.

Fault simulation curve for Example 4.1 at w=2.0.



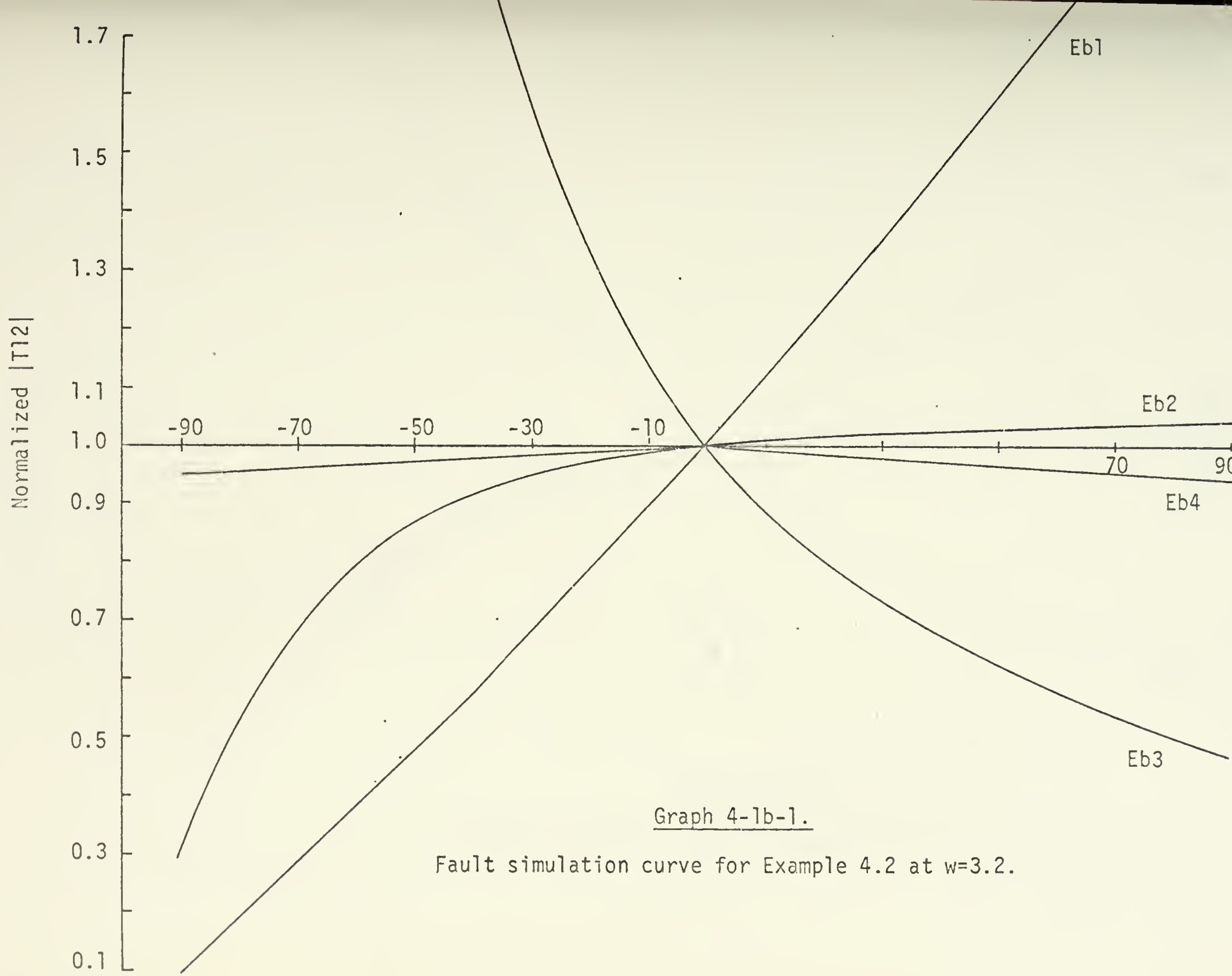
Graph 4-1a-2.

Fault simulation curve for Example 4.1 at w=1.02.



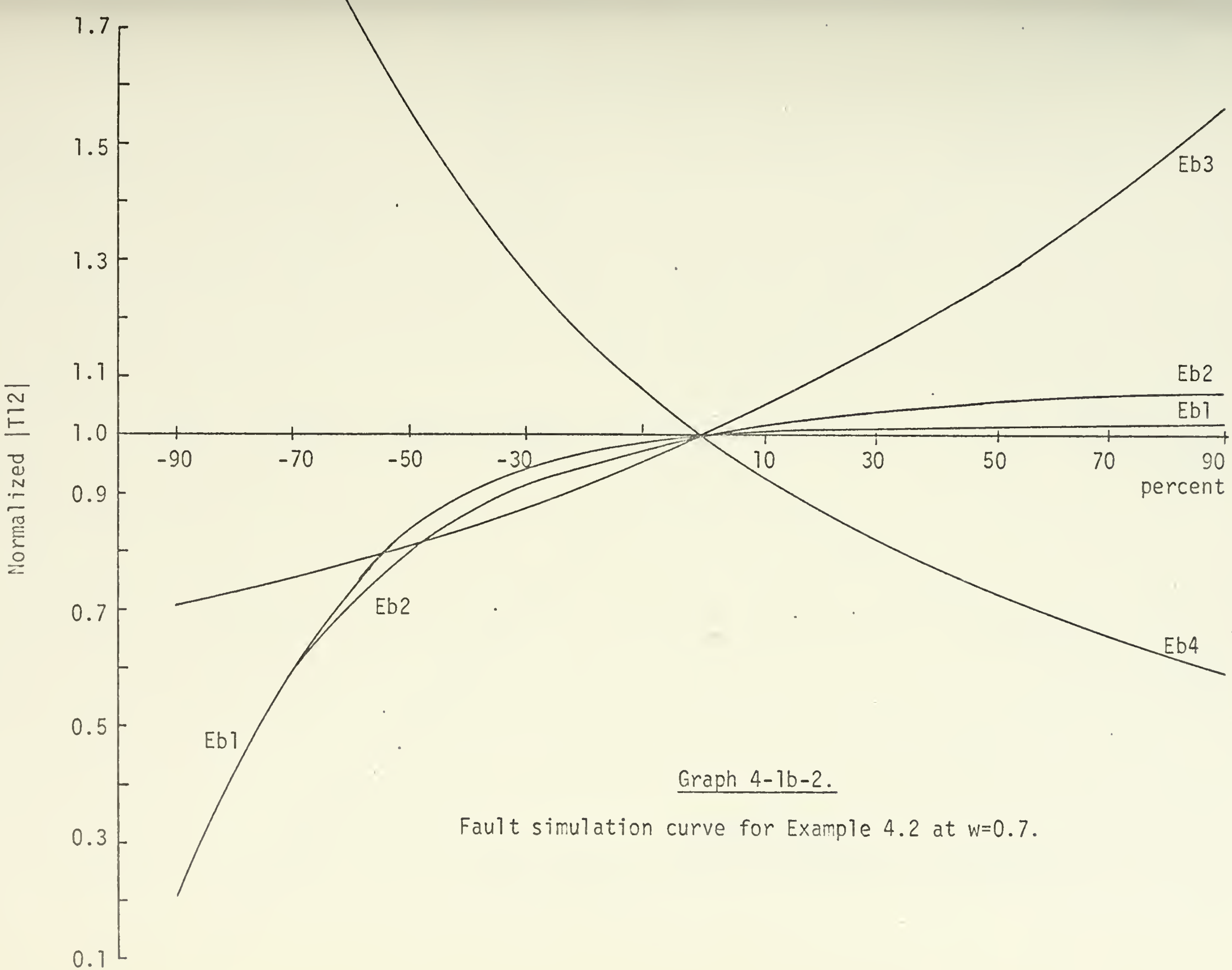
Graph 4-1a-3.

Fault simulation curve for Example 4.1 at w=0.02.



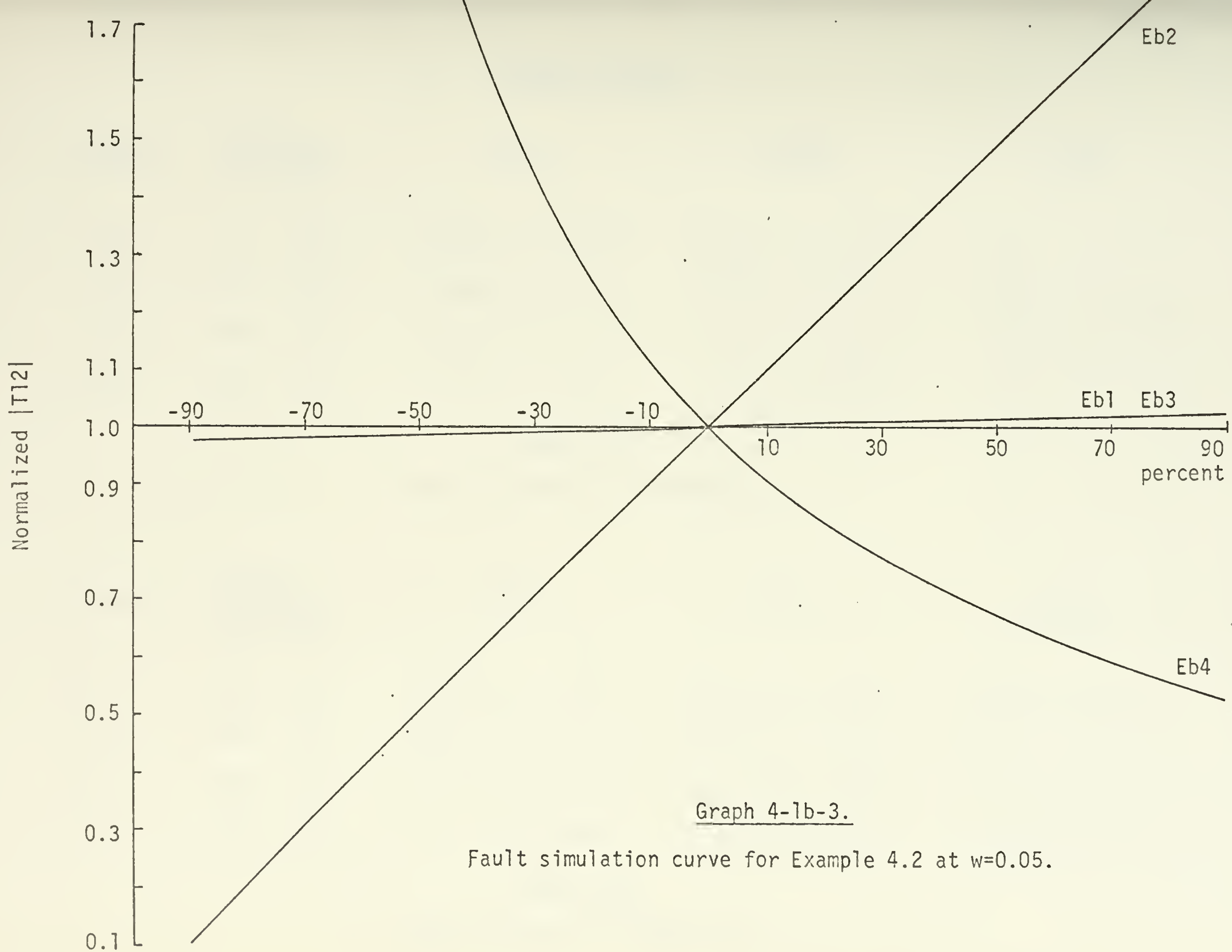
<u>Graph 4-1b-1.</u>

Fault simulation curve for Example 4.2 at w=3.2.



Graph 4-1b-2.

Fault simulation curve for Example 4.2 at w=0.7.



<u>Graph 4-1b-3.</u>

Fault simulation curve for Example 4.2 at w=0.05.

NORMAL REGIONS

Element	Element percentage deviation	x1 (w=2.0)	x2 (w=1.02)	x3 (w=0.02)
Ea1	-20 -- +20	$0.80 \leq x1 \leq 1.20$	$0.80 \leq x2 \leq 1.20$	$0.92 \leq x3 \leq 1.06$
Ea2	-30 -- +25	$0.80 \leq x1 \leq 1.10$	$0.95 \leq x2 \leq 1.05$	$1.02 \geq x3 \geq 0.98$
Ea3	-18 -- +25	$1.20 \geq x1 \geq 0.80$	$1.20 \geq x2 \geq 0.80$	$1.02 \geq x3 \geq 0.98$
Ea4	-20 -- +25	$1.10 \geq x1 \geq 0.90$	$1.05 \geq x2 \geq 0.95$	$1.06 \geq x3 \geq 0.92$

Table 4-2a.

Normal regions for Example 4.1.

Element	Element percentage deviation	x1 (w=3.2)	x2 (w=0.7)	x3 (w=0.05)
Eb1	-28 -- +30	$0.70 \leq x1 \leq 1.35$	$0.95 \leq x2 \leq 1.02$	$0.99 \leq x3 \leq 1.01$
Eb2	-25 -- +30	$0.95 \leq x1 \leq 1.03$	$0.93 \leq x2 \leq 1.05$	$0.77 \leq x3 \leq 1.30$
Eb3	-20 -- +35	$1.35 \geq x1 \geq 0.70$	$0.93 \leq x2 \leq 1.20$	$0.99 \leq x3 \leq 1.01$
Eb4	-25 -- +30	$x1 \geq 0.98$	$1.20 \geq x2 \geq 0.82$	$1.30 \geq x3 \geq 0.77$

Table 4-2b.

Normal regions for Example 4.2.

FAULT IDENTIFICATION REGIONS

Region number	Element percentage deviation	x1 (w=2.0)	x2 (w=1.02)	x3 (w=0.02)
1	Ea1 ↓ -20	$0.80 > x1$	$0.80 > x2$	$0.92 > x3$
2	Ea1 ↑ +20	$x1 > 1.20$	$x2 > 1.20$	$x3 > 1.06$
3	Ea2 ↓ -30	$0.80 > x1$	$0.95 > x2 \geq 0.80$	$1.06 \geq x3 > 1.02$
4	Ea2 ↓ -50	$0.80 > x1$	$0.80 > x2$	$1.06 \geq x3 > 1.02$
5	Ea2 ↑ +25	$1.20 \geq x1 > 1.10$	$1.20 \geq x2 > 1.05$	$0.98 > x3 \geq 0.92$
6	Ea2 ↑ +60	$x1 > 1.20$	$1.20 \geq x2 > 1.05$	$0.98 > x3 \geq 0.92$
7	Ea3 ↑ +25	$0.80 > x1$	$0.80 > x2$	$0.98 > x3 \geq 0.92$
8	Ea3 ↓ -18	$x1 > 1.20$	$x2 > 1.20$	$1.06 \geq x3 > 1.02$
9	Ea4 ↑ +25	$0.90 > x1 \geq 0.80$	$0.95 > x2 \geq 0.80$	$0.92 > x3$
10	Ea4 ↑ +50	$0.80 > x1$	$0.95 > x2 \geq 0.80$	$0.92 > x3$
11	Ea4 ↓ -20	$1.20 \geq x1 > 1.10$	$1.20 \geq x2 > 1.05$	$x3 > 1.06$
12	Ea4 ↓ -40	$x1 > 1.20$	$1.20 \geq x2 > 1.05$	$x3 > 1.06$

Table 4-3a.

Fault identification regions for Example 4.1.

FAULT IDENTIFICATION REGIONS

Region number	Element percentage deviation	x_1 ($w=3.2$)	x_2 ($w=0.7$)	x_3 ($w=0.05$)
1	$E_{b1}\downarrow$ -28	$0.70 > x_1$	$0.95 > x_2 \geq 0.93$	$0.99 > x_3 \geq 0.77$
2	$E_{b1}\downarrow$ -35	$0.70 > x_1$	$0.93 > x_2 \geq 0.82$	$0.99 > x_3 \geq 0.77$
3	$E_{b1}\downarrow$ -50	$0.70 > x_1$	$0.82 > x_2$	$0.99 > x_3 \geq 0.77$
4	$E_{b1}\uparrow$ +30	$x_1 > 1.35$	$1.05 \geq x_2 > 1.02$	$1.30 \geq x_3 > 1.01$
5	$E_{b2}\downarrow$ -25	$0.95 > x_1 \geq 0.70$	$0.93 > x_2 \geq 0.82$	$0.77 > x_3$
6	$E_{b2}\downarrow$ -50	$0.95 > x_1 \geq 0.70$	$0.82 > x_2$	$0.77 > x_3$
7	$E_{b2}\downarrow$ -70	$0.70 > x_1$	$0.82 > x_2$	$0.77 > x_3$
8	$E_{b2}\uparrow$ +30	$1.35 \geq x_1 > 1.03$	$1.30 \geq x_2 > 1.05$	$x_3 > 1.30$
9	$E_{b3}\downarrow$ -20	$x_1 > 1.35$	$0.93 > x_2 \geq 0.82$	$0.99 > x_3 \geq 0.77$
10	$E_{b3}\downarrow$ -50	$x_1 > 1.35$	$0.82 > x_2$	$0.99 > x_3 \geq 0.77$
11	$E_{b3}\uparrow$ +35	$0.70 > x_1$	$x_2 > 1.20$	$1.30 \geq x_3 > 1.01$
12	$E_{b4}\downarrow$ -25	$0.98 > x_1 \geq 0.95$	$x_2 > 1.20$	$x_3 > 1.30$
13	$E_{b4}\uparrow$ +30	$0.98 \geq x_1 \geq 0.95$	$0.82 > x_2$	$0.77 > x_3$

Table 4-3b.

Fault identification regions for Example 4.2.

in Table 4-3a for example 4.1 and Table 4-3b for example 4.2. In Tables 4-3a and 4-3b, an arrow "↑" means "more than" and an arrow "↓" means "less than".

D. CONSTRUCTION OF FAULT IDENTIFICATION MATRIX

The sub-fault identification matrices and the fault identification matrix, M, for the fault identification regions defined in Table 4-3a, are constructed step by step according to the rules given previously. The boundary point values for x_i where i = 1,2,3 are tabulated in Table 4-4.

	B.P.V.'s			
x_1	1.2	1.1	0.9	0.8
x_2	1.2	1.05	0.95	0.8
x_3	1.06	1.02	0.98	0.92

Table 4-4.

The sub-fault identification matrices with respect to x_1 are represented by m_1, m_2, m_3 and m_4 , the sub-fault identification matrices with respect to x_2 are represented by m_5, m_6, m_7 and m_8 and the sub-fault identification matrices with respect to x_3 are represented by m_9, m_{10}, m_{11} and m_{12}. All of the sub-fault identification matrices and M are given as follows.

B.P.V. R- 1 2 3 4 5 6 7 8 9 10 11 12

1.2
$$m_1 = \begin{bmatrix} -1. & 1. & -1. & -1. & -1. & 1. & -1. & 1. & -1. & -1. & -1. & 1. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 1.2 & -1.2 & 1.2 & 1.2 & 1.2 & -1.2 & 1.2 & -1.2 & 1.2 & 1.2 & 1.2 & -1.2 \end{bmatrix}$$

1.1
$$m_2 = \begin{bmatrix} -1. & 1. & -1. & -1. & 1. & 1. & -1. & 1. & -1. & -1. & 1. & 1. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 1.1 & -1.1 & 1.1 & 1.1 & -1.1 & -1.1 & 1.1 & -1.1 & 1.1 & 1.1 & -1.1 & -1.1 \end{bmatrix}$$

0.9
$$m_3 = \begin{bmatrix} -1. & 1. & -1. & -1. & 1. & 1. & -1. & 1. & -1. & -1. & 1. & 1. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0.9 & -0.9 & 0.9 & 0.9 & -0.9 & -0.9 & 0.9 & -0.9 & 0.9 & 0.9 & -0.9 & -0.9 \end{bmatrix}$$

0.8
$$m_4 = \begin{bmatrix} -1. & 1. & -1. & -1. & 1. & 1. & -1. & 1. & 1. & -1. & 1. & 1. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0.8 & -0.8 & 0.8 & 0.8 & -0.8 & -0.8 & 0.8 & -0.8 & -0.8 & 0.8 & -0.8 & -0.8 \end{bmatrix}$$

$$m_1 + m_2 + m_3 + m_4 =$$

$$\begin{bmatrix} -4. & 4. & -4. & -4. & 2. & 4. & -4. & 4. & -2. & -4. & 2. & 4. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 4. & -4. & 4. & 4. & -1.6 & -4. & 4. & -4. & 2.4 & 4. & -1.6 & -4. \end{bmatrix}$$

B.P.V.		R- 1	2	3	4	5	6	7	8	9	10	11	12
1.2		0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
		-1.	1.	-1.	-1.	-1.	-1.	-1.	1.	-1.	-1.	-1.	-1.
	$m_5 =$	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
		1.2	-1.2	1.2	1.2	1.2	1.2	1.2	-1.2	1.2	1.2	1.2	1.2
1.05		0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
		-1.	1.	-1.	-1.	1.	1.	-1.	1.	-1.	-1.	1.	1.
	$m_6 =$	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
		1.05	-1.05	1.05	1.05	-1.05	-1.05	1.05	-1.05	1.05	1.05	-1.05	-1.05
0.95		0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
		-1.	1.	-1.	-1.	1.	1.	-1.	1.	-1.	-1.	1.	1.
	$m_7 =$	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
		0.95	-0.95	0.95	0.95	-0.95	-0.95	0.95	-0.95	0.95	0.95	-0.95	-0.95
0.80		0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
		-1.	1.	1.	-1.	1.	1.	-1.	1.	1.	1.	1.	1.
	$m_8 =$	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
		0.8	-0.8	-0.8	0.8	-0.8	-0.8	0.8	-0.8	-0.8	-0.8	-0.8	-0.8

$m_5 + m_6 + m_7 + m_8 =$

0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
-4.	4.	-2.	-4.	2.	2.	-4.	4.	-2.	-2.	-2.	-2.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
4.	-4.	2.4	4.	-1.6	-1.6	4.	-4.	2.4	2.4	-1.6	-1.6

$$
\begin{array}{ll}
 & \begin{array}{cccccccccccc} \text{R- }1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \end{array} \\
\text{B.P.V.} & \\
1.06 & \\
m_9 = & \begin{bmatrix} 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ -1. & 1. & -1. & -1. & -1. & -1. & -1. & -1. & -1. & -1. & 1. & 1. \\ 1.06 & -1.06 & 1.06 & 1.06 & 1.06 & 1.06 & 1.06 & 1.06 & 1.06 & 1.06 & -1.06 & -1.06 \end{bmatrix} \\
1.02 & \\
m_{10} = & \begin{bmatrix} 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ -1. & 1. & 1. & 1. & -1. & -1. & -1. & 1. & -1. & -1. & 1. & 1. \\ 1.02 & -1.02 & -1.02 & -1.02 & 1.02 & 1.02 & 1.02 & -1.02 & 1.02 & 1.02 & -1.02 & -1.02 \end{bmatrix} \\
0.98 & \\
m_{11} = & \begin{bmatrix} 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\ -1. & 1. & 1. & 1. & -1. & -1. & -1. & 1. & -1. & -1. & 1. & 1. \\ 0.98 & -0.98 & -0.98 & -0.98 & 0.98 & 0.98 & 0.98 & -0.98 & 0.98 & 0.98 & -0.98 & -0.98 \end{bmatrix}
\end{array}
$$

$$
\begin{array}{ll}
 & \begin{array}{cccccccccccc} \text{R- }1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \end{array} \\
\begin{array}{l} \text{B.P.V.} \\ 0.92 \\ m_{12} = \end{array} &
\begin{bmatrix}
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
-1. & 1. & 1. & 1. & 1. & 1. & 1. & 1. & -1. & -1. & 1. & 1. \\
0.92 & -0.92 & -0.92 & -0.92 & -0.92 & -0.92 & -0.92 & -0.92 & 0.92 & 0.92 & -0.92 & -0.92
\end{bmatrix}
\end{array}
$$

$$m_9 + m_{10} + m_{11} + m_{12} =$$

$$
\begin{bmatrix}
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
-4. & 4. & 2. & 2. & -2. & -2. & -2. & 2. & -4. & -4. & 4. & 4. \\
3.98 & -3.98 & -1.86 & -1.86 & 2.14 & 2.14 & 2.14 & -1.86 & 3.98 & 3.98 & -3.98 & -3.98
\end{bmatrix}
$$

$$M = m_1 + m_2 + m_3 + m_4 + \text{-----------------} + m_{12}$$

$$
M = \begin{bmatrix}
-4. & 4. & -4. & -4. & 2. & 4. & -4. & 4. & -2. & -4. & 2. & 4. \\
-4. & 4. & -2. & -4. & 2. & 2. & -4. & 4. & -2. & -2. & 2. & 2. \\
-4. & 4. & 2. & 2. & -2. & -2. & -2. & 2. & -4. & -4. & 4. & 4. \\
11.98 & -11.98 & 4.54 & 6.14 & -1.06 & -3.46 & 10.14 & -9.86 & 8.78 & 10.38 & -7.18 & -9.58
\end{bmatrix}
$$

E. GENERATION OF $\overline{X}$

The components of $\overline{X}$ can be obtained by the measurements of the normalized $|T12|$ corresponding to the chosen test frequencies.

Suppose that it is desired to determine which element is faulty in a network accessible only at the input and output terminals. The diagnosis of the network malfunction can be accomplished using the fault identification matrix.

The value of $\overline{X}$ will fall in one of the defined fault identification regions.

F. GENERATION OF $\overline{Z}$ AND FAULT IDENTIFICATION

The generation of $\overline{Z}$ and the fault identification are best seen by the following three cases for example 4.1.

Case 1. Let the measured values of the components of $\overline{X}$ at the selected test frequencies w_1, w_2 and w_3 be

$$x_1 = .6$$

$$x_2 = .7$$

$$x_3 = .9$$

$\overline{Z}$ is generated as follows.

$$\overline{Z}' = \overline{X}'M$$

$$= [\ .6 \quad .7 \quad .9 \quad 1.\ ]\ M$$

$$\bar{Z} = \begin{bmatrix} -2.4 & -2.8 & -3.6 & +11.98 \\ 2.4 & +2.8 & +3.6 & +11.98 \\ -2.4 & -1.4 & +1.8 & +4.54 \\ -2.4 & -2.8 & +1.8 & +6.14 \\ 1.2 & +1.4 & -1.8 & -1.06 \\ 2.6 & +1.4 & -1.8 & -3.46 \\ -2.4 & -2.8 & -1.8 & +10.14 \\ 2.4 & +2.8 & +1.8 & -9.86 \\ -1.2 & -1.4 & -3.6 & +8.78 \\ -2.4 & -1.4 & -3.6 & +10.38 \\ 1.2 & +1.4 & +3.6 & -7.18 \\ 2.4 & +1.4 & +3.6 & -9.58 \end{bmatrix} = \begin{bmatrix} 3.18 \\ -3.18 \\ 2.54 \\ 2.74 \\ -0.26 \\ -1.46 \\ 3.14 \\ -2.86 \\ 2.58 \\ 2.98 \\ -0.98 \\ -2.18 \end{bmatrix} = \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \\ z_6 \\ z_7 \\ z_8 \\ z_9 \\ z_{10} \\ z_{11} \\ z_{12} \end{bmatrix}$$

Case 2. If the measured values of the components of $\bar{X}$ at the selected test frequencies are

$$x_1 = 1.3$$

$$x_2 = 1.1$$

$$x_3 = 0.95$$

$$\begin{aligned} \bar{Z}' &= \bar{X}'M \\ &= [\ 1.3 \quad 1.1 \quad .95 \quad 1.\ ]\ M \\ &= [\ -1.42 \quad 1.42 \quad -.96 \quad -1.56 \quad 1.84 \quad 2.04 \\ &\qquad -1.36 \quad 1.64 \quad .18 \quad -.82 \quad 1.42 \quad 1.62\ ] \\ &= [\ z_1 \quad z_2 \quad z_3 \quad z_4 \quad z_5 \quad z_6 \\ &\qquad z_7 \quad z_8 \quad z_9 \quad z_{10} \quad z_{11} \quad z_{12}\ ] \end{aligned}$$

Case 3. If the measured values of the components of $\overline{X}$ at the selected test frequencies are

$$x_1 = 2.$$

$$x_2 = 1.1$$

$$x_3 = .98$$

$$\begin{aligned} \overline{Z}' &= \overline{X}'M \\ &= [\,2. \quad 1.1 \quad .98 \quad 1.\,]\,M \\ &= [\,-4.34 \quad 4.34 \quad -3.7 \quad -4.3 \quad 3.18 \quad 4.78 \\ &\qquad -4.22 \quad 4.5 \quad -1.34 \quad -3.74 \quad 2.94 \quad 4.54\,] \\ &= [\,z_1 \quad z_2 \quad z_3 \quad z_4 \quad z_5 \quad z_6 \\ &\qquad z_7 \quad z_8 \quad z_9 \quad z_{10} \quad z_{11} \quad z_{12}\,] \end{aligned}$$

From the defined fault identification regions, Table 4-3a, the following facts are known for each case.

Case 1. The algebraically largest component in $\overline{Z}$ is the component z_1. The network is operating in R-1 which means Ea1 is deviated less than -20 percent from the nominal value. In example 4.1, R_1 is out of tolerance.

Case 2. The component z_6 in $\overline{Z}$ is the algebraically largest component. The network is operating in R-6. The element Ea2 is deviated more than 60 percent from the nominal value. In example 4.1, L is out of tolerance.

Case 3. The component z_6 in $\overline{Z}$ is the algebraically largest component again but the noticeable fact is that the value of the component z_6 is different from that of the previous case. The relative value of the component of $\overline{Z}$ may suggest the degree of violation of the faulty element.

The method discussed in the foregoing illustrations is called the single element fault identification method. A combined element fault identification, abbreviated by C. E. F. I., method is a method in which more than one element fault is identified.

The algorithm of the single element fault identification method is suitable for computer implementation. If the fault identification regions are properly defined, then the construction of M and the generation of $\overline{Z}$ are matrix operations. The fault identification is the comparison of the values of the components in $\overline{Z}$.

A program for the single element fault identification, designated by program 1, is written as shown in Appendix A and its implementation is annexed in Appendix B. The results of the computer applications for example 4.1 are shown in Fig. 4-3, Fig. 4-4 and Fig. 4-5. The same procedures are used for example 4.2 and the results of the computer applications are shown in Fig. 4-6, Fig. 4-7 and Fig. 4-8.

DEFINED BOUNDARY POINT VALUES

NUMBER OF FREQUENCIES NV= 3

NUMBER OF REGIONS NR= 12

LOWER B.P.V.	UPPER B.P.V.
0.0	0.80000
0.0	0.80000
0.0	0.92000
1.20000	100.00000
1.20000	100.00000
1.06000	100.00000
0.0	0.80000
0.80000	0.95000
1.02000	1.06000
0.0	0.80000
0.0	0.80000
1.02000	1.06000
1.10000	1.20000
1.05000	1.20000
0.92000	0.98000
1.20000	100.00000
1.05000	1.20000
0.92000	0.98000
0.0	0.80000
0.0	0.80000
0.92000	0.98000
1.20000	100.00000
1.20000	100.00000
1.02000	1.06000
0.80000	0.90000
0.80000	0.95000
0.0	0.92000
0.0	0.80000
0.80000	0.95000
0.0	0.92000
1.10000	1.20000
1.05000	1.20000
1.06000	100.00000
1.20000	100.00000
1.05000	1.20000
1.06000	100.00000

Fig. 4-3.

Fault identification regions

printed by computer for Example 4.1.

FAULT IDENTIFICATION MATRIX

$$
\left[\begin{array}{rrrrrrrrrr}
-3.00 & 5.00 & -3.00 & -3.00 & 3.00 & 5.00 & -3.00 & 5.00 & -1.00 & -3.00 \\
-3.00 & 5.00 & -1.00 & -3.00 & 3.00 & 3.00 & -3.00 & 5.00 & -1.00 & -1.00 \\
-3.00 & 5.00 & 3.00 & 3.00 & -1.00 & -1.00 & -1.00 & 3.00 & -3.00 & -3.00 \\
11.98 & -11.98 & 4.54 & 6.14 & -1.06 & -3.46 & 10.14 & -9.86 & 8.78 & 10.38
\end{array}\right.
$$

$$
\left.\begin{array}{rr}
3.00 & 5.00 \\
3.00 & 3.00 \\
5.00 & 5.00 \\
-7.18 & -9.58
\end{array}\right]
$$

Fig. 4-4.

Fault identification matrix

generated by computer for Example 4.1.

```
VECTOR X                                    VECTOR Z

0.60     0.70     0.90     1.00

     5.38    -0.98     4.74     4.94     1.94     0.74     5.34    -0.66     4.78     5.18
     1.22     0.02
                                    FAULT IDENTIFICATION REGION  1,

1.30     1.10     0.95     1.00

     1.93     4.77     2.39     1.79     5.19     5.39     1.99     4.99     3.53     2.53
     4.77     4.97
                                    FAULT IDENTIFICATION REGION  6,

2.00     1.10     0.98     1.00

    -0.26     8.42     0.38    -0.22     7.26     8.86    -0.14     8.58     2.74     0.34
     7.02     8.62
                                    FAULT IDENTIFICATION REGION  6,
```

Fig. 4-5.

Table of vector-Z for Example 4.1.

DEFINED BOUNDARY POINT VALUES

NUMBER OF FREQUENCIES NV= 3

NUMBER OF REGIONS . NR= 13

LOWER B.P.V.	UPPER B.P.V.
0.0	0.70000
0.93000	0.95000
0.77000	0.99000
0.0	0.70000
0.82000	0.93000
0.77000	0.99000
0.0	0.70000
0.0	0.82000
0.77000	0.99000
1.35000	100.00000
1.02000	1.05000
1.01000	1.30000
0.70000	0.95000
0.82000	0.93000
0.0	0.77000
0.70000	0.95000
0.0	0.82000
0.0	0.77000
0.0	0.70000
0.0	0.82000
0.0	0.77000
1.03000	1.35000
1.05000	1.30000
1.30000	100.00000
1.35000	100.00000
0.82000	0.93000
0.77000	0.99000
1.35000	100.00000
0.0	0.82000
0.77000	0.99000
0.0	0.70000
1.20000	100.00000
1.01000	1.30000
0.95000	0.98000
1.20000	100.00000
1.30000	100.00000
0.95000	0.98000
0.0	0.82000
0.0	0.77000

Fig. 4-6.

Fault identification regions

printed by computer for Example 4.2.

FAULT IDENTIFICATION MATRIX

$$
\begin{bmatrix}
-4.00 & -4.00 & -4.00 & 6.00 & -2.00 & -2.00 & -4.00 & 4.00 & 6.00 & 6.00 \\
-2.00 & -4.00 & -6.00 & 2.00 & -4.00 & -6.00 & -6.00 & 4.00 & -4.00 & -6.00 \\
-1.00 & -1.00 & -1.00 & 3.00 & -3.00 & -3.00 & -3.00 & 5.00 & -1.00 & -1.00 \\
11.31 & 13.17 & 14.81 & -6.65 & 13.31 & 14.95 & 16.35 & -8.65 & 3.15 & 4.79 \\
\\
-4.00 & 0.0 & 0.0 \\
8.00 & 8.00 & -6.00 \\
3.00 & 5.00 & -3.00 \\
-3.73 & -9.63 & 13.05
\end{bmatrix}
$$

Fig. 4-7.

Fault identification matrix

generated by computer for Example 4.2.

VECTOR X VECTOR Z

0.60	0.94	0.80	1.00						
6.23	6.21	5.97	1.23	5.95	5.71	5.91	1.51	2.19	1.95
3.79	1.89	5.01							
			FAULT IDENTIFICATION REGION 1,						
0.60	0.8C	0.80	1.00						
6.51	6.77	6.81	0.95	6.51	6.55	6.75	0.95	2.75	2.79
2.67	C.77	5.85							
			FAULT IDENTIFICATION REGION 3,						
2.00	1.30	1.20	1.00						
-0.49	-1.23	-2.19	11.55	0.51	-0.45	-3.05	10.55	8.75	7.79
2.27	6.77	1.65							
			FAULT IDENTIFICATION REGION 4,						

Fig. 4-8.

Table of vector-Z for Example 4.2.

V. COMBINED ELEMENT FAULT IDENTIFICATION

Multi-element fault identification, abbreviated by M.E.F.I., is a somewhat complicated task. However, if multi-element fault simulation, abbreviated by M.E.F.S., for a certain system can be made, M.E.F.I. is possible.

Consider the number of times of M.E.F.S. necessary for a M.E.F.I.. For a 3-element system, using the abbreviation for the combination of m elements out of n elements, nCm, the number of times to be simulated is as follows.

3C1 = 3 --- one element fault combinations

3C2 = 3 --- two elements fault combinations

3C3 = 1 --- three elements fault combination

Including every element deviation of 10 times, each element deviation from -90 percent to +90 percent of the nominal value with 20 percent of step size, the number of fault simulations necessary for a M.E.F.I. is as many as

3C1	10			=	30	for one element fault simulations
3C2	10	10		=	300	for two elements fault simulations
3C3	10	10	10	=	1000	for three elements fault simulations
					1330	for total number of fault simulations

Thus, a total of 1330 multi-element fault simulations are required even in a simple 3-element system.

The number of possible M.E.F.S. required for a M.E.F.I. is shown in Table 5-1 and it becomes astronomical as the number of elements increases.

No. of element	No. of M.E.F.S.
2	110
3	1330
4	14640
5	161050
6	1771560

Table 5-1.

This astronomical increase of M.E.F.S. discourages one to make any further investigation. However, another method can take its place as is explained as follows. A complex system can be partitioned properly such that the probability of failure involving more than one element at a time is usually small.

In this section, the combined element fault identification (C.E.F.I.) method is introduced. A complex network shown in Fig. 5-1 is partitioned properly into two subnetworks shown in Fig. 5-2. Two subnetworks NW-1 and NW-2 are regarded as independent and the single element fault identification method can be applied to each network.

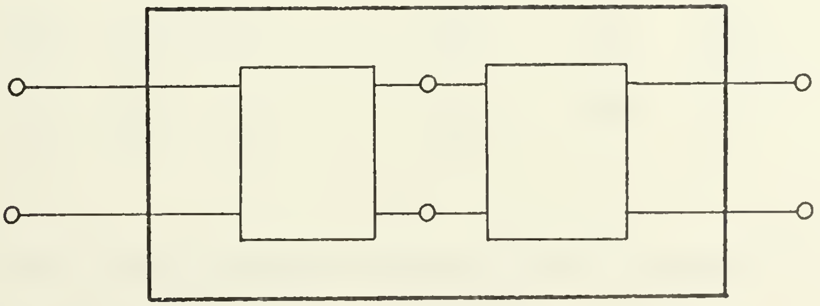


Fig. 5-1.

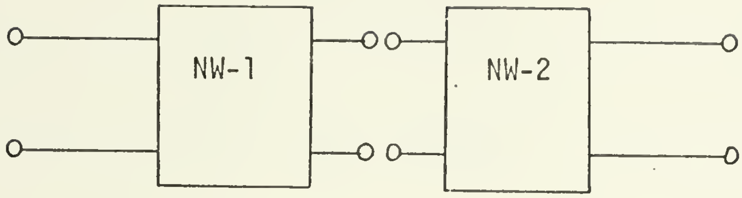


Fig. 5-2.

Suppose that the fault identification matrices for NW-1 and NW-2 are constructed and designated by

M1 for NW-1

M2 for NW-2

Let M be defined as

$$M = \left[\begin{array}{c|c} M1 & 0 \\ \hline 0 & M2 \end{array}\right] \tag{5-1}$$

The measured values of the components of $\overline{X}$ can be obtained with respect to a set of selected test frequencies for NW-1 and NW-2 independently and designated as follows.

$x_{11}, \ x_{12}, \ x_{13}, \ \text{-----}, \ x_{1n},$ for NW-1

$x_{21}, \ x_{22}, \ x_{23}, \ \text{-----}, \ x_{2m},$ for NW-2

where n and m are the number of selected test frequencies for NW-1 and NW-2 respectively. Then $\overline{Z}$ are generated as follows.

$$\overline{Z}' = \overline{X}'M = \overline{X1}', \overline{X2}' \begin{bmatrix} M1 & \vdots & 0 \\ \cdots & & \cdots \\ 0 & \vdots & M2 \end{bmatrix} = \overline{X1}'M1, \overline{X2}'M2$$

$$= [\ z_1 \quad z_2 \quad z_3 \text{ ---- } z_{rd} \quad z_{(rd+1)} \text{ ---- } z_r\ ]$$

where

$$\overline{X}' = \overline{X1}', \overline{X2}'$$

$$\overline{X1}' = [\ x_{11} \quad x_{12} \quad x_{13} \text{ ----- } x_{1n} \quad 1.\ ]$$

$$\overline{X2}' = [\ x_{21} \quad x_{22} \quad x_{23} \text{ ----- } x_{2m} \quad 1.\ ]$$

$$\overline{Z1}' = \overline{X1}'M1 = [\ z_1 \quad z_2 \quad z_3 \text{ --- } z_{rd}\ ]$$

$$\overline{Z2}' = \overline{X2}'M2 = [\ z_{(rd+1)} \text{ ------ } z_r\ ]$$

r is the total number of fault identification regions for both networks and rd and r-rd are the number of fault identification regions for NW-1 and NW-2 respectively. $\overline{Z}$ will indicate two faulty elements. One from $\overline{Z1}$ indicates a fault in NW-1 and the other one from $\overline{Z2}$ indicates a fault in NW-2.

This is the C.E.F.I. method for two elements fault identification. The C.E.F.I. method can be extended to isolate multi-element faults.

For example, suppose that the network shown in Fig. 4-1a is replaced by NW-1 and the network shown in Fig. 4-1b is replaced by NW-2 for C.E.F.I. and the fault identification matrix for NW-1 is M1 and the fault identification matrix for NW-2 is M2. The resulting M is constructed by Eq. (5-1) and shown in Fig. 5-3.

Let the measured values of the components of $\overline{X}$ be

$$\overline{X}1' = [\, x_{11} \quad x_{12} \quad x_{13} \quad 1. \,] = [\, 0.6 \quad 0.7 \quad 0.9 \quad 1. \,]$$

$$\overline{X}2' = [\, x_{21} \quad x_{22} \quad x_{23} \quad 1. \,] = [\, 0.6 \quad 0.94 \quad 0.8 \quad 1. \,]$$

$$\overline{X}' = \overline{X}1', \overline{X}2' = [\, 0.6 \quad 0.7 \quad 0.9 \quad 1. \quad 0.6 \quad 0.94 \quad 0.8 \quad 1. \,]$$

$\overline{Z}'$ becomes

$$\overline{Z}' = \overline{X}'M = \overline{X}1'M1, \overline{X}2'M2$$

$$\begin{aligned} \overline{Z}' = [\, & 3.18 \quad -3.18 \quad 2.54 \quad 2.74 \quad -0.26 \quad -1.46 \quad 3.14 \quad -2.86 \\ & 2.58 \quad 2.98 \quad -0.98 \quad -2.18 \quad 3.89 \quad 3.87 \quad 3.63 \quad -1.11 \\ & 3.61 \quad 3.37 \quad 3.57 \quad -0.83 \quad -0.15 \quad -0.39 \quad 1.45 \quad -0.45 \\ & 2.67 \,] \end{aligned}$$

$$= [\, z_1 \quad z_2 \quad z_3 \quad ----- \quad z_{12} \quad z_{13} \quad ----- \quad z_{25} \,]$$

One fault identification region from R-1 ----- R-12, represented by z_1 ----- z_{12} respectively, indicates a fault in NW-1 and the other one fault identification region from R-13 ----- R-25, represented by z_{13} ----- z_{25} respectively, indicates a fault in NW-2. In this example, the albegraically largest component among z_1 ----- z_{12} is z_1 and the largest component among z_{13} ----- z_{25} is z_{13}. The fault identification region R-1 indicates that Ea1 in NW-1 is deviated less than -20 percent from the nominal value. The fault identification region R-13 represents R-1 in NW-2 because NW-1 has 12 fault identification regions and indicates that Eb1 is deviated less than -28 percent from the nominal value. Two more examples are presented in Fig. 5-4.

A program for C.E.F.I., designated by program 2, is written as shown in Appendix A and its implementation is annexed in Appendix B.

-4.00	4.00	-4.00	-4.00	2.00	4.00	-4.00	4.00	-2.00	-4.00
-4.00	4.00	-2.00	-4.00	2.00	2.00	-4.00	4.00	-2.00	-2.00
-4.00	4.00	2.00	2.00	-2.00	-2.00	-2.00	2.00	-4.00	-4.00
11.98	-11.98	4.54	6.14	-1.06	-3.46	10.14	-9.86	8.78	10.38
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

2.00	4.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.00	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-7.18	-9.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	-5.00	-5.00	-5.00	5.00	-3.00	-3.00	-5.00	3.00
0.0	0.0	-3.00	-5.00	-7.00	1.00	-5.00	-7.00	-7.00	3.00
0.0	0.0	-2.00	-2.00	-2.00	2.00	-4.00	-4.00	-4.00	4.00
0.0	0.0	11.31	13.17	14.81	-6.65	13.31	14.95	16.35	-8.65

0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0
5.00	5.00	-5.00	-1.00	-1.00
-5.00	-7.00	7.00	7.00	-7.00
-2.00	-2.00	2.00	4.00	-4.00
3.15	4.79	-3.73	-9.63	13.05

Fig. 5-3.

Fault identification matrix for C.E.F.I.

```
VECTOR X                                    VECTOR Z

0.60     0.70     0.90     1.00     0.60     0.94     0.80     1.00

    3.18    -3.18     2.54     2.74    -0.26    -1.46     3.14    -2.86     2.58     2.98
   -0.98    -2.18     3.89     3.87     3.63    -1.11     3.61     3.37     3.57    -0.83
   -0.15    -C.39     1.45    -0.45     2.67
                          FAULT IDENTIFICATION REGION 13,
                          FAULT IDENTIFICATION REGION  1,

1.30     1.10     0.95     1.00     0.60     0.80     0.80     1.00

   -1.42     1.42    -0.96    -1.56     1.84     2.04    -1.36     1.64     0.18    -0.82
    1.42     1.62     4.31     4.57     4.61    -1.25     4.31     4.35     4.55    -1.25
    0.55     0.59     0.47    -1.43     3.65
                          FAULT IDENTIFICATION REGION 15,
                          FAULT IDENTIFICATION REGION  6,

2.00     1.10     0.98     1.00     2.00     1.30     1.20     1.00

   -4.34     4.34    -3.70    -4.30     3.18     4.78    -4.22     4.50    -1.34    -3.74
    2.94     4.54    -4.99    -5.73    -6.69     7.05    -3.99    -4.95    -7.55     6.05
    4.25     3.29    -2.23     2.27    -2.85
                          FAULT IDENTIFICATION REGION 16,
                          FAULT IDENTIFICATION REGION  6,
```

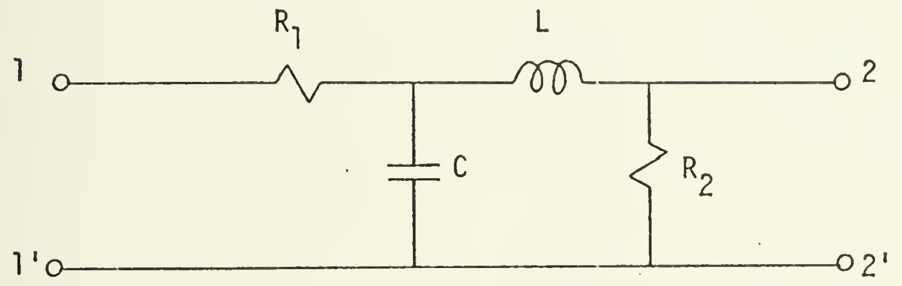
Fig. 5-4.

Table of vector-Z for C.E.F.I.

VI. EXPERIMENTS

A. PASSIVE LINEAR NETWORK EXPERIMENT

The network shown in Fig. 6-1 (identical to that of Fig. 4-1a) was used in the experiment.



$R_1 = 2$ ohms

$L = 2$ henry

$C = 3$ farads

$R_2 = 4$ ohms

Fig. 6-1.

Passive network

The following relationships are used for frequency and magnitude scaling:

$$R^* = b\,R$$

$$L^* = b/a\,L$$

$$C^* = 1/ab\,C$$

$$f^* = a\,f$$

where "a" is the frequency scale factor (dimensionless, real and

positive constant), "b" is the magnitude scale factor (dimensionless, real and positive constant) and a scaled nominal element value is identified by an asterisk superscript.

With $a = 10000$ and $b = 100$, the scaled nominal element values were

$$1/Ea1 = R_1 = 200 \text{ ohms}$$

$$1/Ea2 = L = 20 \text{ milli henry}$$

$$Ea3 = C = 3 \text{ micro farads}$$

$$1/Ea4 = R_2 = 400 \text{ ohms}$$

and a set of 3 selected test frequencies became

$$w_1 = 20000 \text{ radians/sec}, \quad f_1 = 3185 \text{ Hz}$$

$$w_2 = 10200 \text{ radians/sec}, \quad f_2 = 1624 \text{ Hz}$$

$$w_3 = 200 \text{ radians/sec}, \quad f_3 = 31.8 \text{ Hz}$$

The experimental results for fault simulations at a set of selected frequencies were tabulated in Table 6-1 for the network shown in Fig. 6-1. Comparing Table 6-1 with Table 4-1a and taking into consideration the accuracy of the measuring devices, it is concluded that the experimental results in Table 6-1 and the theoretical results in Table 4-1a are close.

Consider the following four cases.

Case 1. If the resistor, R_1, was changed to 130 ohms from the nominal value of 200 ohms, the magnitudes of T12 were 0.0935, 0.222 and 0.755 at a set of 3 selected test frequencies f_1, f_2 and f_3

respectively. Since the nominal magnitudes of T12 were the same as used in Section IV-C, the normalized magnitudes of T12 became

$$x_1 = 1.562$$

$$x_2 = 1.515$$

$$x_3 = 1.138$$

Case 2. If the inductor, L, was changed to 30 milli henry from the nominal value of 20 milli henry, the magnitudes of T12 at a set of 3 selected frequencies were 0.0462 , 0.131 and 0.664. The normalized magnitudes of T12 were

$$x_1 = 0.777$$

$$x_2 = 0.891$$

$$x_3 = 1.0$$

Case 3. If the capacitor, C, was changed to 4 micro farads, the magnitudes of T12 were 0.448 , 0.109 and 0.664 and the normalized magnitudes of T12 were

$$x_1 = 0.748$$

$$x_2 = 0.743$$

$$x_3 = 0.98$$

Case 4. If it was made that the resistor, R_2, changed to 250 ohms, the magnitudes of T12 were 0.0453 , 0.13 and 0.56 and the normalized magnitudes of T12 were

$$x_1 = 0.757$$

$$x_2 = 0.889$$

$$x_3 = 0.84$$

Using the fault identification matrix, Fig. 4-4, $\overline{Z}$ and the fault identification were generated as shwon in Fig. 6-1.

From Fig. 6-1 and the defined fault identification regions, Table 4-3a, the following facts were known for each case.

Case 1. The component z_2 was the largest component in $\overline{Z}$ and $\overline{X}$ belonged to the fault identification region R-2. Ea1 was deviated more than 20 percent from the nominal value. R_1 was out of tolerance.

Case 2. The network was operating in R-3. Ea2 was deviated to somewhere between -30 percent and -50 percent from the nominal value. L was out of tolerance.

Case 3. The network was operating in R-7 and Ea3 was deviated more than 25 percent. C was out of tolerance.

Case 4. Ea4 was deviated more than 50 percent which was indicated by R-10.

B. ACTIVE LINEAR NETWORK EXPERIMENT

The network shown in Fig. 6-2 was used for active linear network experiment. The frequency response of the active network was drawn in Fig. 6-3 using the computer program ECAP. A set of selected test frequencies was chosen as follows.

$$f_1 = 10 \text{ Hz}$$

$$f_2 = 100 \text{ Hz}$$

$$f_3 = 1000 \text{ Hz}$$

Element	DEV (percent)		Element value		MAG-T1 (at f_1)	MAG-T2 (at f_2)	MAG-T3 (at f_3)	NOR-T1	NOR-T2	NOR-T3
Ea1	90	R_1	105.	ohms	0.10800	0.26200	0.80000	1.8048	1.7882	1.2035
	70		117.8		0.09700	0.24000	0.77500	1.6209	1.6380	1.1659
	50		133.3		0.08930	0.21500	0.75000	1.4923	1.4674	1.1283
	30		154.		0.07690	0.18700	0.72500	1.2851	1.2763	1.0907
	10		182.		0.06570	0.16000	0.69000	1.0979	1.0920	1.0380
	-10		222.		0.05400	0.13200	0.64100	0.9024	0.9009	0.9643
	-30		286.		0.04200	0.10200	0.58000	0.7019	0.6962	0.8726
	-50		400.		0.02950	0.07300	0.49500	0.4930	0.4982	0.7447
	-70		666.		0.01780	0.04300	0.37000	0.2975	0.2935	0.5566
	-90		2000.		0.00550	0.01430	0.15500	0.0919	0.0976	0.2332
Ea2	90	L	10.5	mh	0.07430	0.15600	0.66400	1.2416	1.0647	0.9989
	70		11.7		0.07310	0.15500	0.66400	1.2216	1.0579	0.9989
	50		13.3		0.07020	0.15400	0.66400	1.1731	1.0511	0.9989
	30		15.4		0.06680	0.15200	0.66400	1.1163	1.0374	0.9989
	10		18.2		0.06300	0.14800	0.66400	1.0528	1.0101	0.9989
	-10		22.2		0.05680	0.14300	0.66500	0.9492	0.9760	1.0004
	-30		28.6		0.04870	0.13300	0.66500	0.8138	0.9077	1.0004
	-50		40.		0.03680	0.11600	0.66500	0.6150	0.7917	1.0004
	-70		66.6		0.02300	0.08100	0.66500	0.3843	0.5528	1.0004
	-90		200.		0.00830	0.02900	0.66500	0.1387	0.1979	1.0004
Ea3	90	C	5.7	µf	0.03100	0.07700	0.65900	0.5180	0.5255	0.9914
	70		5.1		0.03460	0.08600	0.66100	0.5782	0.5870	0.9944
	50		4.5		0.03950	0.09700	0.66300	0.6601	0.6620	0.9974
	30		3.9		0.04550	0.11100	0.66400	0.7603	0.7576	0.9989
	10		3.3		0.05410	0.13300	0.66400	0.9041	0.9077	0.9989
	-10		2.7		0.06720	0.16400	0.66400	1.1230	1.1193	0.9989
	-30		2.1		0.08790	0.21000	0.66500	1.4689	1.4333	1.0004
	-50		1.5		0.12100	0.28300	0.66500	2.0220	1.9315	1.0004
	-70		.9		0.19900	0.41000	0.66500	3.3254	2.7983	1.0004
	-90		.3		0.44900	0.60800	0.66600	7.5031	4.1497	1.0019
Ea4	90	R_2	210.	ohms	0.03950	0.12200	0.51500	0.6601	0.8327	0.7748
	70		235.		0.04300	0.12800	0.54100	0.7186	0.8736	0.8139
	50		266.		0.04720	0.13300	0.57400	0.7887	0.9077	0.8635
	30		308.		0.05160	0.13900	0.61000	0.8623	0.9487	0.9177
	10		364.		0.05710	0.14300	0.64500	0.9542	0.9760	0.9703
	-10		445.		0.06310	0.14900	0.68900	1.0545	1.0169	1.0365
	-30		571.		0.06940	0.15300	0.73900	1.1597	1.0442	1.1118
	-50		800.		0.07530	0.15700	0.79700	1.2583	1.0716	1.1990
	-70		1332.		0.08030	0.16000	0.86900	1.3419	1.0920	1.3073
	-90		4000.		0.08360	0.16100	0.94900	1.3970	1.0989	1.4277

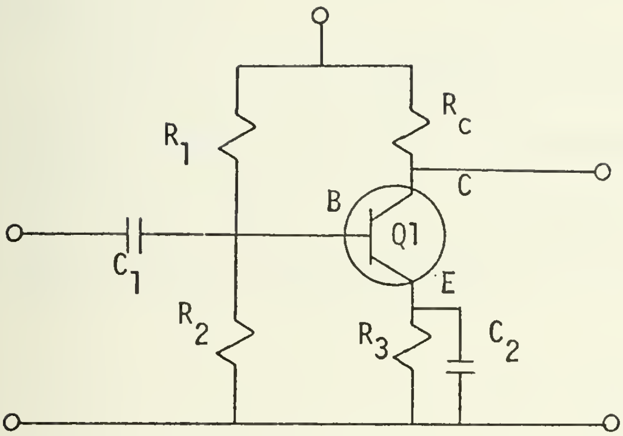
Table 6-1.

Experimental fault simulated data for Passive network

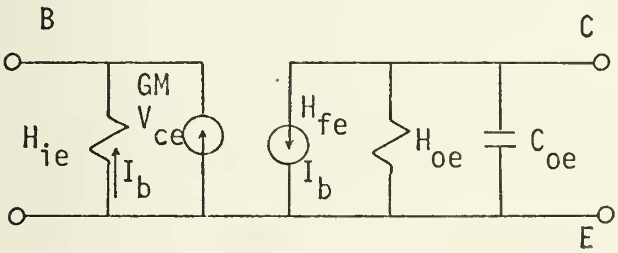
```
VECTOR X                                  VECTOR Z

1.56     1.51     1.14     1.00
    -0.67     9.09     1.75     0.32     7.03     7.76    -0.23     8.94     2.29     0.76
     7.74     8.46
                                   FAULT IDENTIFICATION REGION  2,

0.78     0.89     1.00     1.00
     3.98     1.36     4.32     4.14     2.94     2.10     4.14     1.48     4.11     4.16
     2.82     1.98
                                   FAULT IDENTIFICATION REGION  3,

0.75     0.74     0.98     1.00
     4.57     0.38     4.49     4.61     2.43     1.53     4.69     0.54     4.35     4.45
     2.19     1.29
                                   FAULT IDENTIFICATION REGION  7,

0.76     0.89     0.84     1.00
     4.52     0.45     3.90     3.72     3.04     2.15     4.36     0.89     4.61     4.70
     1.96     1.07
                                   FAULT IDENTIFICATION REGION 10,
```

Fig. 6-1.

Table of Vector-Z for passive network experiment.



(a)



(b) small signal ECAP
equivalent circuit for Q1

R_1 = 100 K ohms
R_2 = 10 K ohms
R_3 = 1 K ohms
R_c = 5 K ohms

C_1 = 5 μf
C_2 = 50 μf

Q1 --- 2N1414

H_{ie} = 1300 ohms
$1/H_{oe}$ = 36 K ohms
H_{re} = $2.9\ 10^{-4}$
H_{fe} = 42

C_{oe} = 26 pf

GM = H_{re}/H_{ie}

Fig. 6-2.

Active network

Since there was no computer program available for fault simulations of the active case, the necessary data were obtained from the experimental results. The fault simulated data were tabulated in Table 6-2. The fault simulation curves were drawn in Graph 6-1, Graph 6-2 and Graph 6-3. The normal regions were defined in Table 6-3 and the fault identification regions were defined in Table 6-4. The fault identification

matrix was generated by the program 1 (in Appendix A) and is shown in Fig. 6-5.

$\bar{Z}$ and the fault identification were obtained for the following three cases.

Case 1. Let the resistor, R_2, be changed to 14 K ohms from the nominal value of 10 K ohms. The measured magnitudes of T12 were 11.71 , 91.0 and 179.0 at 3 test frequencies f_1 , f_2 and f_3 respectively. Then the normalized magnitudes of T12 became

$$x_1 = 1.03$$

$$x_2 = 1.08$$

$$x_3 = 1.26$$

Case 2. If the resistor, R_c, was changed to 7 K ohms from the nominal value of 5 K ohms, the measured magnitudes of T12 were 15.9 , 126.0 and 190.2 at 3 corresponding test frequencies. The normalized magnitudes of T12 were

$$x_1 = 1.39$$

$$x_2 = 1.5$$

$$x_3 = 1.34$$

Case 3. If the capacitor, C_2, was changed to 35 micro farads from the nominal value of 50 micro farads, the measured magnitudes of T12 were 9.5 , 75.0 and 143.0 at 3 corresponding test frequencies. The normalized magnitudes of T12 were

$$x_1 = 0.834$$

$$x_2 = 0.892$$

$$x_3 = 1.007$$

Using M, shown in Fig. 6-5, $\overline{Z}$ and the fault identification generated by the computer (program 1) are shwon in Fig. 6-6.

From the defined fault identification regions, Table 6-4, the following facts were known for each case.

Case 1. The component z_3 was the algebraically largest component in $\overline{Z}$. R-3 indicated that R_2 was deviated more than 30 percent.

Case 2. The fault identification region R-8 indicated that R_c was deviated more than 20 percent.

Case 3. The fault identification region R-13 indicated that C_2 was deviated between 40 percent and 70 percent.

C. PASSIVE AND ACTIVE NETWORK C.E.F.I. EXPERIMENT

Suppose that the networks shown in Fig. 6-1 and Fig. 6-2 were considered as an interconnection of two-port network consisting of two cascade connected subnetworks and regarding Fig. 6-1 as NW-1 and Fig. 6-2 as NW-2, The fault identification matrix for C.E.F.I. experiment were shown in Fig. 6-7.

Applying the same procedures as in the C.E.F.I. method previously discussed, the network malfunctions could be isolated. The C.E.F.I. was accomplished for three cases with the same $\overline{X}$ used in the passive and active network single element fault identification experiments. The resulted fault identification was shown in Fig. 6-8.

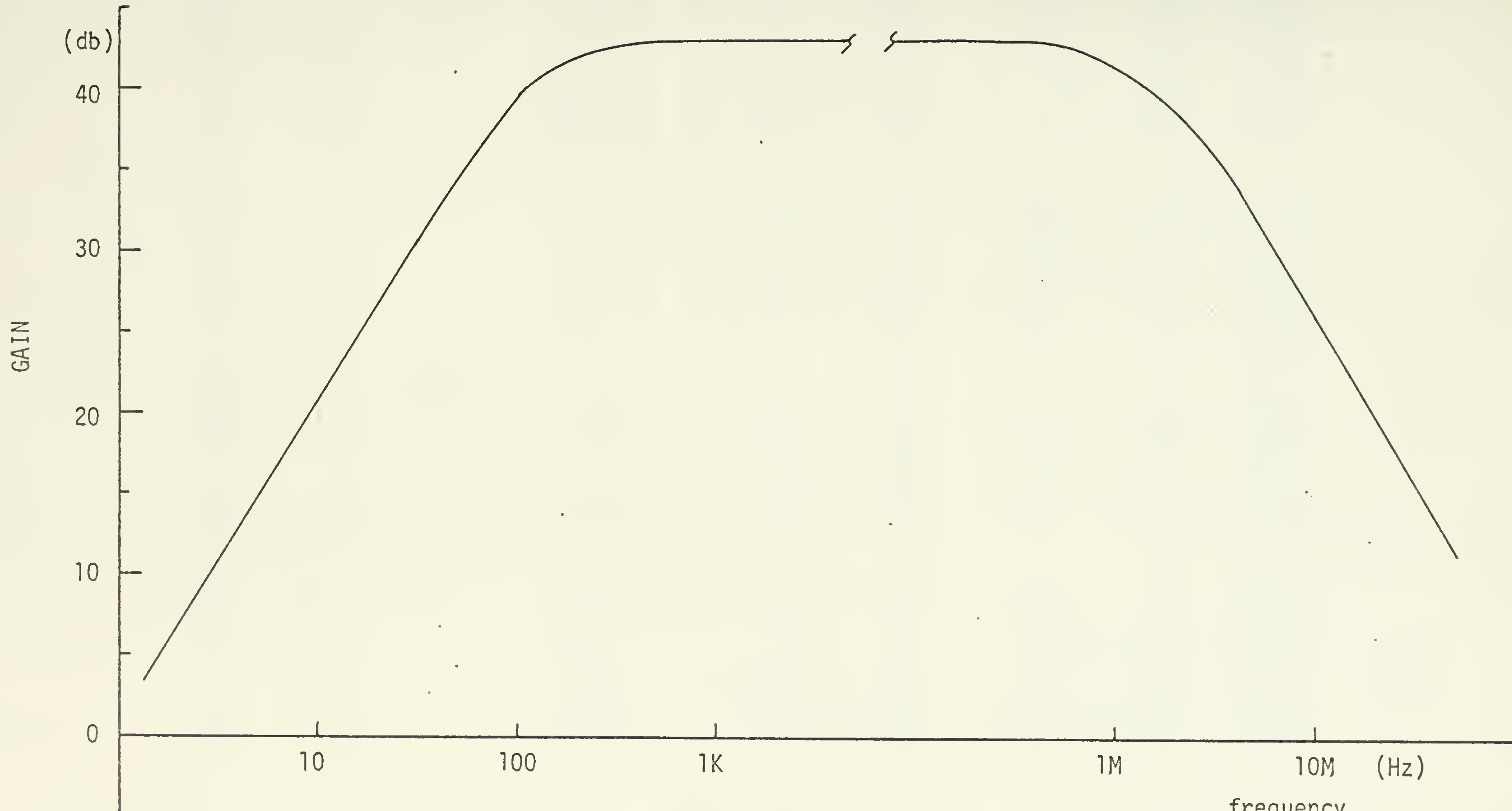


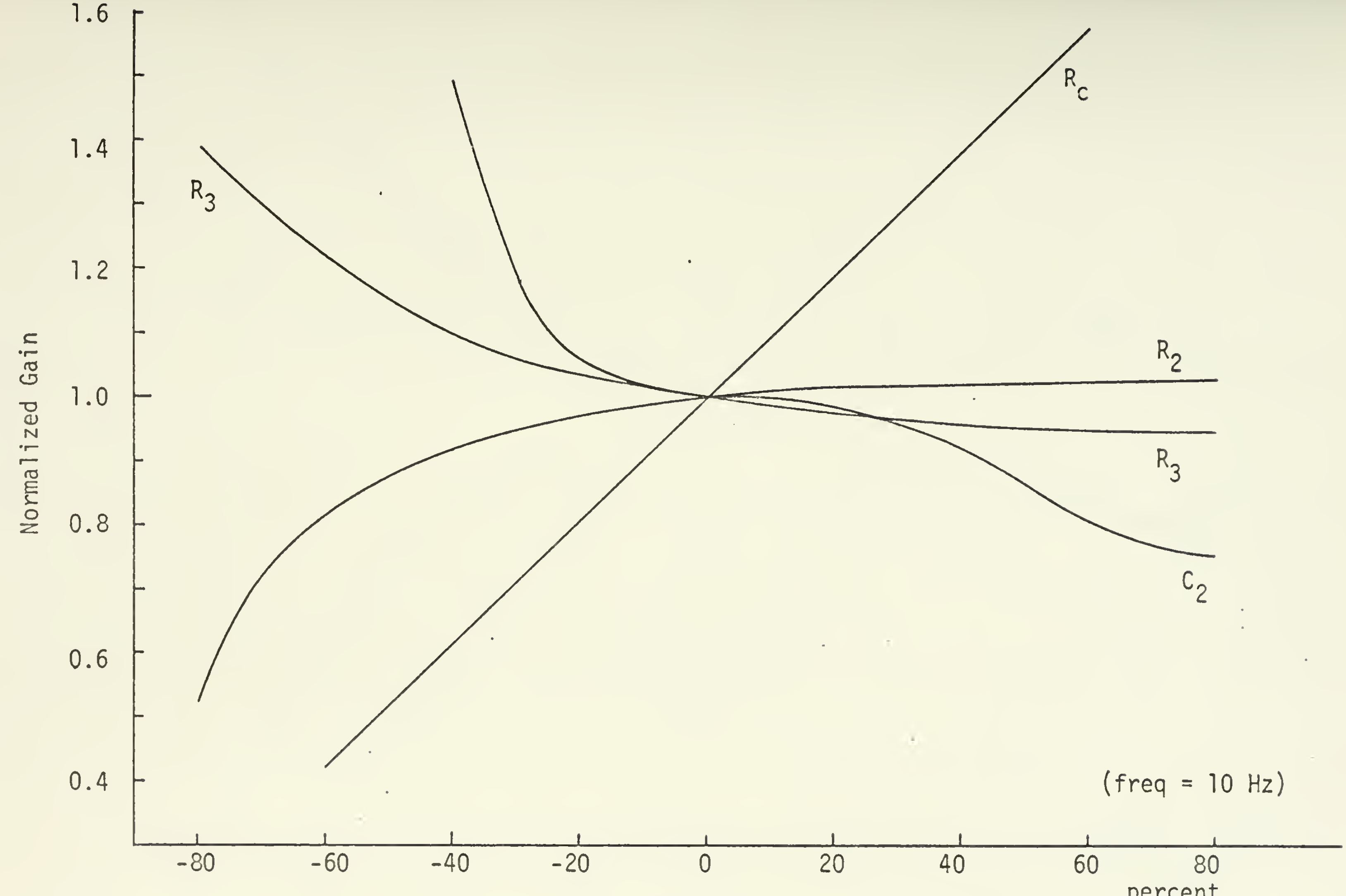
Fig. 6-3.

Frequency response for active network.

Element	DEV (percent)	Element Value	MAG-T1 (at f_1)	MAG-T2 (at f_2)	MAG-T3 (at f_3)	NCR-T1	NOR-T2	NOR-T3
R_2	-80	2. K ohms	6.0000	25.0000	27.0000	0.5263	0.2976	0.1901
	-60	4.	9.2000	51.0000	61.5000	0.8070	0.6071	0.4331
	-40	6.	10.5000	68.5000	93.5000	0.9211	0.8155	0.6585
	-20	8.	11.0500	78.5000	120.0000	0.9693	0.9345	0.8451
	0	10.	11.4000	84.0000	142.0000	1.0000	1.0000	1.0000
	20	12.	11.6000	88.5000	160.0000	1.0175	1.0536	1.1268
	40	14.	11.7000	90.0000	178.0000	1.0263	1.0714	1.2535
	60	16.	11.7000	92.0000	191.0000	1.0263	1.0952	1.3451
	80	18.	11.7000	94.0000	203.5000	1.0263	1.1190	1.4331
R_3	-80	.2 K ohms	15.2000	99.0000	260.0000	1.3333	1.1786	1.8310
	-60	.4	14.0000	94.0000	230.5000	1.2281	1.1190	1.6232
	-40	.6	12.5000	91.5000	199.5000	1.0965	1.0893	1.4049
	-20	.8	11.8000	89.5000	166.0000	1.0351	1.0655	1.1690
	0	1.	11.4000	84.0000	142.0000	1.0000	1.0000	1.0000
	20	1.2	11.1000	80.0000	125.0000	0.9737	0.9524	0.8803
	40	1.4	11.0000	75.0000	110.0000	0.9649	0.8929	0.7746
	60	1.6	10.9000	70.0000	99.5000	0.9561	0.8333	0.7007
	80	1.8	10.8000	67.5000	89.5000	0.9474	0.8036	0.6303
R_c	-80	1. K ohms	2.5000	15.0000	87.5000	0.2193	0.1786	0.6162
	-60	2.	4.8000	31.5000	92.5000	0.4211	0.3750	0.6514
	-40	3.	7.0000	49.5000	102.0000	0.6140	0.5893	0.7183
	-20	4.	9.1000	67.0000	116.0000	0.7982	0.7976	0.8169
	0	5.	11.4000	84.0000	142.0000	1.0000	1.0000	1.0000
	20	6.	13.6000	100.0000	168.5000	1.1930	1.1905	1.1866
	40	7.	15.8000	117.0000	192.5000	1.3860	1.3929	1.3556
	60	8.	17.9000	132.0000	215.0000	1.5702	1.5714	1.5141
	80	9.	20.0000	147.5000	233.0000	1.7544	1.7560	1.6408
$1/C_2$	-80	250. µf	37.0000	140.0000	140.0000	3.2456	1.6667	0.9859
	-60	125.	23.2000	121.0000	140.3000	2.0351	1.4405	0.9880
	-40	83.5	17.0000	105.0000	140.7000	1.4912	1.2500	0.9908
	-20	62.5	12.0000	88.0000	141.0000	1.0526	1.0476	0.9930
	0	50.	11.4000	84.0000	142.0000	1.0000	1.0000	1.0000
	20	41.6	11.3000	82.5000	142.3000	0.9912	0.9821	1.0021
	40	35.7	10.5000	79.0000	142.7000	0.9211	0.9405	1.0049
	60	31.2	9.2000	71.5000	143.0000	0.8070	0.8512	1.0070
	80	27.8	8.6000	66.0000	143.5000	0.7544	0.7857	1.0106

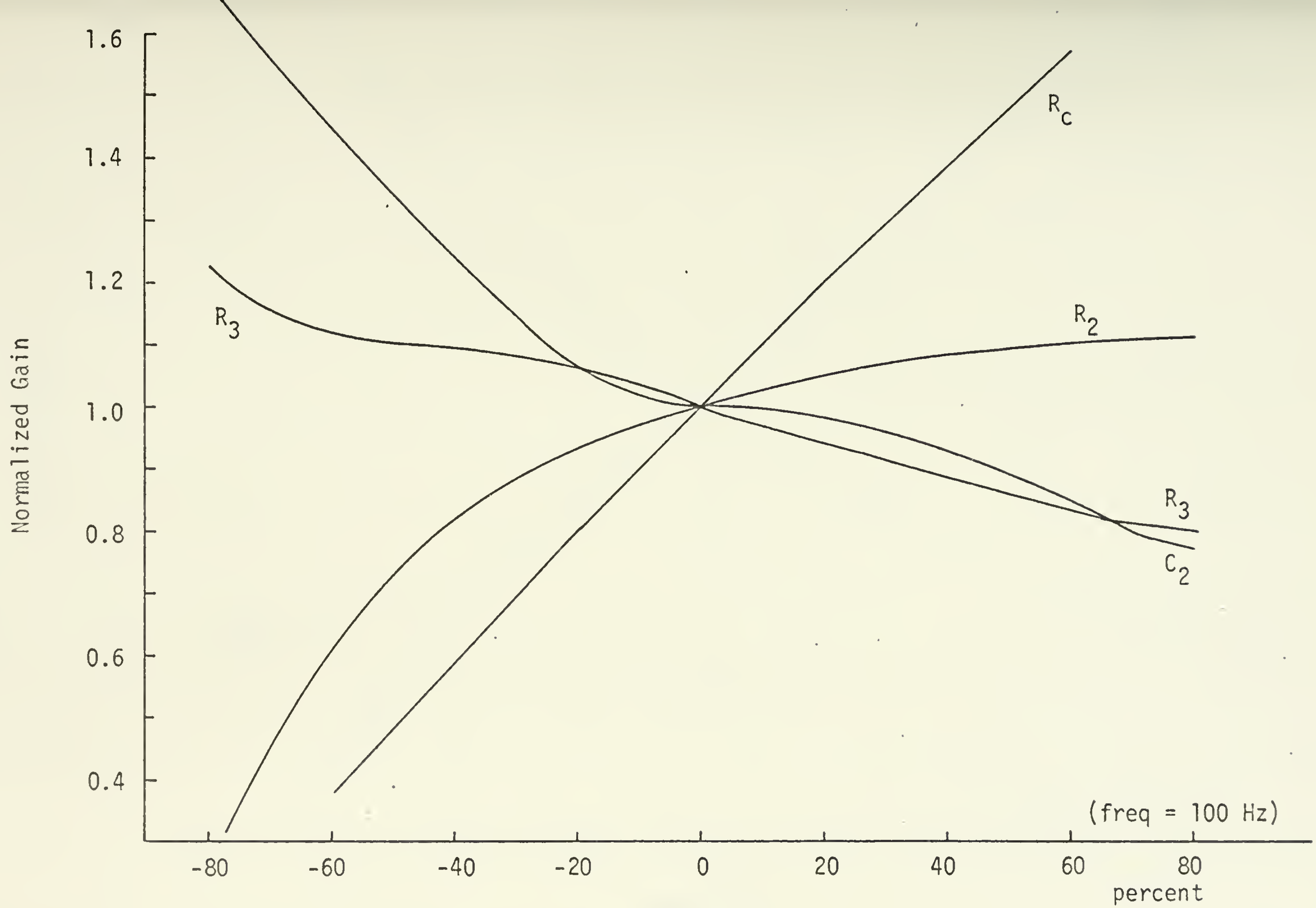
Table 6-2.

Experimental fault simulated data for Active network.



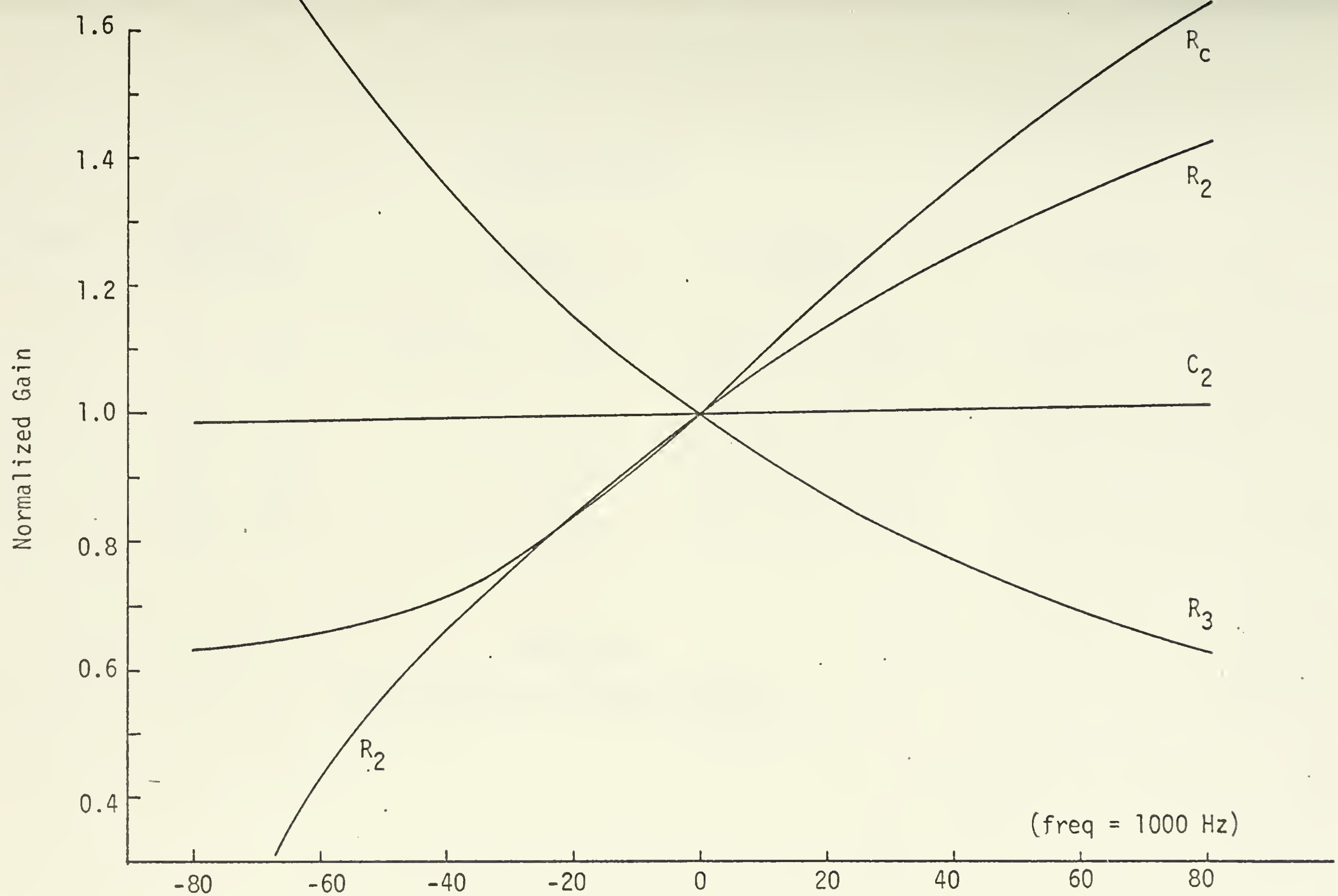
Graph 6-1.

Experimental fault simulation curve for Active network.



Graph 6-2.

Experimental fault simulation curve for Active network.



Graph 6-3.

Experimental fault simulation curve for Active network.

NORMAL REGIONS

Element	Element percentage deviation	x1 (f=10)	x2 (f=100)	x3 (f=1000)
R2	-40 -- +30	$0.92 \leq x1 \leq 1.02$	$0.80 \leq x2 \leq 1.07$	$0.66 \leq x3 \leq 1.20$
R3	-25 -- +25	$1.05 \geq x1 \geq 0.97$	$1.07 \geq x2 \geq 0.93$	$1.20 \geq x3 \geq 0.84$
R_c	-20 -- +20	$0.80 \leq x1 \leq 1.20$	$0.80 \leq x2 \leq 1.20$	$0.84 \leq x3 \leq 1.20$
C_2	-20 -- +25	$1.05 \geq x1 \geq 0.97$	$1.07 \geq x2 \geq 0.97$	$0.99 \leq x3 \leq 1.01$

Table 6-3.

Normal regions for Active network.

FAULT IDENTIFICATION REGIONS

Region number	Element percentage deviation		x1 (f=10)	x2 (f=100)	x3 (f=1000)
1	R2	-40	$0.92 > x1 \geq 0.80$	$0.80 > x2$	$0.66 > x3$
2	R2	-60	$0.80 > x1$	$0.80 > x2$	$0.66 > x3$
3	R2	+30	$1.05 \geq x1 > 1.02$	$1.20 \geq x2 > 1.07$	$x3 > 1.20$
4	R3	-25	$1.20 \geq x1 > 1.05$	$1.20 \geq x2 > 1.07$	$x3 > 1.20$
5	R3	-55	$x1 > 1.20$	$1.20 \geq x2 > 1.07$	$x3 > 1.20$
6	R3	+25	$0.97 > x1 \geq 0.92$	$0.93 > x2 \geq 0.80$	$0.84 > x3 \geq 0.66$
7	Rc	-20	$0.80 > x1$	$0.80 > x2$	$0.84 > x3 \geq 0.66$
8	Rc	+20	$x1 > 1.20$	$x2 > 1.20$	$x3 > 1.20$
9	C2	-20	$1.20 \geq x1 > 1.05$	$1.20 \geq x2 > 1.07$	$0.99 > x3 \geq 0.84$
10	C2	-30	$x1 > 1.20$	$x2 > 1.20$	$0.99 > x3 \geq 0.84$
11	C2	-70	$x1 > 1.20$	$x2 > 1.20$	$0.84 > x3 \geq 0.66$
12	C2	+25	$0.97 > x1 \geq 0.92$	$0.97 > x2 \geq 0.93$	$1.20 \geq x3 > 1.01$
13	C2	+40	$0.92 > x1 \geq 0.80$	$0.93 > x2 \geq 0.80$	$1.20 \geq x3 > 1.01$
14	C2	+70	$0.80 > x1$	$0.80 > x2$	$1.20 \geq x3 > 1.01$

Table 6-4.

Fault identification regions for Active network

DEFINED BOUNDARY POINT VALUES

NUMBER OF FREQUENCIES NV= 3

NUMBER OF REGIONS NR= 14

LOWER B.P.V.	UPPER B.P.V.
0.80000	0.92000
0.0	0.80000
0.0	0.66000
0.0	0.80000
0.0	0.80000
0.0	0.66000
1.02000	1.05000
1.07000	1.20000
1.20000	100.00000
1.05000	1.20000
1.07000	1.20000
1.20000	100.00000
1.20000	100.00000
1.07000	1.20000
1.20000	100.00000
0.92000	0.97000
0.80000	0.93000
0.66000	0.84000
0.0	0.80000
0.0	0.80000
0.66000	0.84000
1.20000	100.00000
1.20000	100.00000
1.20000	100.00000
1.05000	1.20000
1.07000	1.20000
0.84000	0.99000
1.20000	100.00000
1.20000	100.00000
0.84000	0.99000
1.20000	100.00000
1.20000	100.00000
0.66000	0.84000
0.92000	0.97000
0.93000	0.97000
1.01000	1.20000
0.80000	0.92000
0.80000	0.93000
1.01000	1.20000
0.0	0.80000
0.0	0.80000
1.01000	1.20000

Fig. 6-4.

Fault identification regions

printed by computer for Active network.

FAULT IDENTIFICATION MATRIX

$$
\begin{bmatrix}
-3.00 & -5.00 & 3.00 & 5.00 & 7.00 & -1.00 & -5.00 & 7.00 & 5.00 & 7.00 & 7.00 & -1.00 & -3.00 & -5.00 \\
-4.00 & -4.00 & 4.00 & 4.00 & 4.00 & -2.00 & -4.00 & 6.00 & 4.00 & 6.00 & 6.00 & 0.0 & -2.00 & -4.00 \\
-4.00 & -4.00 & 6.00 & 6.00 & 6.00 & -2.00 & -2.00 & 6.00 & 0.0 & 0.0 & -2.00 & 4.00 & 4.00 & 4.00 \\
14.03 & 15.63 & -8.73 & -10.83 & -13.23 & 9.27 & 14.31 & -15.63 & -4.43 & -9.23 & -7.55 & 1.73 & 5.43 & 8.63
\end{bmatrix}
$$

Fig. 6-5.

Fault identification matrix

generated by computer for Active network.

```
VECTOR X                            VECTOR Z

1.03   1.08   1.26   1.00
   1.58   1.12   6.24   6.20   5.86   3.56   2.32   5.62   5.04   4.46
   3.62   5.74   5.22   4.20
                          FAULT IDENTIFICATION REGION  3,

1.39   1.50   1.34   1.00
  -1.50  -2.68   9.48  10.16  10.54   2.20  -1.32  11.14   8.52   9.50
   8.50   5.70   3.62   1.04
                          FAULT IDENTIFICATION REGION  8,

0.83   0.89   1.01   1.00
   3.93   3.86   3.38   2.95   2.22   4.64   4.56   1.60   3.31   1.96
   1.63   4.92   5.17   4.92
                          FAULT IDENTIFICATION REGION 13,
```

Fig. 6-6.

Table of vector-Z for Active network.

-4.00	4.00	-4.00	-4.00	2.00	4.00	-4.00	4.00	-2.00	-4.00
-4.00	4.00	-2.00	-4.00	2.00	2.00	-4.00	4.00	-2.00	-2.00
-4.00	4.00	2.00	2.00	-2.00	-2.00	-2.00	2.00	-4.00	-4.00
11.98	-11.98	4.54	6.14	-1.06	-3.46	10.14	-9.86	8.78	10.38
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

2.00	4.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2.00	2.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.00	4.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
-7.18	-9.58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	-4.00	-6.00	2.00	4.00	6.00	-2.00	-6.00	6.00
0.0	0.0	-5.00	-5.00	3.00	3.00	3.00	-3.00	-5.00	5.00
0.0	0.0	-5.00	-5.00	5.00	5.00	5.00	-3.00	-3.00	5.00
0.0	0.0	14.03	15.63	-8.73	-10.83	-13.23	9.27	14.31	-15.63

0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0
4.00	6.00	6.00	-2.00	-4.00	-6.00
3.00	5.00	5.00	-1.00	-3.00	-5.00
-1.00	-1.00	-3.00	3.00	3.00	3.00
-4.43	-9.23	-7.55	1.73	5.43	8.63

<u>Fig. 6-7.</u>

Fault identification matrix for

C.E.F.I. experiment

```
VECTOR X                                VECTOR Z

1.56     1.51     1.14     1.00     1.03     1.08     1.26     1.00

   -4.88     4.88    -2.46    -3.89     2.82     3.54    -4.44     4.72    -1.93    -3.45
    3.53     4.25    -1.79    -2.25     2.87     2.83     2.49     0.19    -1.05     2.25
    1.67     1.09     0.25     2.37     1.85     0.83
                         FAULT IDENTIFICATION REGION  2,
                         FAULT IDENTIFICATION REGION 15,

0.78     0.89     1.00     1.00     1.39     1.50     1.34     1.00

    1.31    -1.31     1.65     1.47     0.28    -0.57     1.47    -1.19     1.44     1.49
    0.16    -0.69    -5.73    -6.91     5.25     5.93     6.31    -2.03    -5.55     6.91
    4.29     5.27     4.27     1.47    -0.61    -3.19
                         FAULT IDENTIFICATION REGION 20,
                         FAULT IDENTIFICATION REGION  3,

0.75     0.74     0.98     1.00     0.83     0.89     1.01     1.00

    2.10    -2.10     2.02     2.14    -0.04    -0.94     2.22    -1.94     1.88     1.98
   -0.28    -1.18     1.20     1.13     0.65     0.22    -0.52     1.91     1.83    -1.13
    0.57    -0.77    -1.11     2.19     2.44     2.19
                         FAULT IDENTIFICATION REGION 25,
                         FAULT IDENTIFICATION REGION  7,
```

Fig. 6-8.

Table of vector-Z for C.E.F.I. experiment.

VII. FEASIBILITY OF FAULT PREDICTION

The feasibility study of fault prediction is quite complicated. However a brief discussion of this topic is included in this section.

Suppose that M of a certain system is

$$M = \begin{bmatrix} a_{11} & a_{12} & a_{13} & ----- & a_{1j} & ----- & a_{1r} \\ a_{21} & a_{22} & a_{23} & ----- & a_{2j} & ----- & a_{2r} \\ \\ a_{n1} & a_{n2} & a_{n3} & ----- & a_{nj} & ----- & a_{nr} \\ A_1 & A_2 & A_3 & ----- & A_j & ----- & A_r \end{bmatrix}$$

and $\overline{X}'$ is

$$\overline{X}' = [\, x_1 \;\; x_2 \;\; x_3 \;\; --- \;\; x_i \;\; --- \;\; x_n \;\; 1. \,]$$

$\overline{Z}'$ becomes

$$\overline{Z}' = \overline{X}'M = [\, x_1 \;\; x_2 \;\; ----- \;\; x_n \;\; 1. \,]\, M$$

$$= [\, z_1 \;\; z_2 \;\; --- \;\; z_j \;\; --- \;\; z_r \,]$$

where

$$z_j = x_1a_{1j} + x_2a_{2j} + --------- + x_na_{nj} + A_j \qquad j=1,2,---,r$$

x_i is positive real number (i=1,2,---,n) and a_{ij} and A_j are real constants.

Since z_j is linear functions of x_is, the variation of the value of z_j is monotonic.

If the system is faulty and z_j is algebraically the largest component, the system is operating in R-j and an element which is out of tolerance can be isolated from the predefined fault identification regions.

Taking the network shown in Fig. 4-1a as an example for the fault prediction, there are 8 boundary point values between the normal region and the faulty region at a test frequency. The largest components in $\bar{Z}$ at these boundary point values are shown in Table 7-1. From this table

Element (percentage)		x_1 (at boundary)	x_2	x_3	The largest component in $\bar{Z}$ at boundary
Ea1	(-20)	(0.80	0.80	0.91)	1.90
Ea1	(+20)	(1.20	1.20	1.06)	1.86
Ea2	(-30)	(0.80	0.95	1.02)	1.48
Ea2	(+25)	(1.10	1.05	0.98)	1.28
Ea3	(-18)	(1.20	1.20	1.02)	1.78
Ea3	(+25)	(0.80	0.80	0.98)	1.78
Ea4	(-20)	(1.10	1.05	1.06)	1.36
Ea4	(+25)	(0.90	0.95	0.92)	1.40

Table 7-1.

the following observations are made:

1) If the deviation of Ea1 element is to be decreased less than -20 percent, the largest component in $\bar{Z}$ must be algebraically greater than 1.90; if the deviation of Ea1 element increased more than +20 percent, the largest component in $\bar{Z}$ must be greater than 1.86. The same idea can be applied to all elements.

2) If z_j for all j is smaller than 1.28, the smallest value in Table 7-1, the network is working in normal condition.

3) If z_j for all j is larger than 1.90, the largest value in Table 7-1, the network is working in one of the faulty regions.

4) If the largest component z_j in $\overline{Z}$ is in between 1.28 and 1.90, the network may or may not be in a normal region. For instance, if the largest component z_j is 1.50 and the network is still in normal condition, then it is known that Ea2 and Ea4 are not faulty and Ea1 or Ea3 may begin to approach one of the faulty regions. If the largest component z_j is 1.50 and the network is in faulty condition, then it is known that Ea2 is faulty.

VIII. CONCLUSION

A fault identification technique has been investigated in this paper. Although the examples used are simple, the fault identification procedures presented here may be extended to more complex systems.

The theoretical basis of the proposed method is described and the technique has been applied to both passive and active networks.

The main differences in the approach used in this paper for fault identification over the gain signature approach cited in References [3], [8] and [10] are summarized as follows.

1). Fault identification regions are defined uniquely according to the fault simulation curves which are constructed from the system sensitivity instead of assignment of gain signature.

2). Direct application of the measured values for fault isolation can be accomplished instead of gain signature conversion.

3). Vector-Z indicates an exact faulty element automatically rather than a gain signature comparison.

4). The selection of a set of test frequencies is not critical as in the gain signature approach.

5). By applying the matrix operation to the fault identification matrix of the single element fault identification method, one can detect not only a fault of the one-element type but also a multi-element fault in the given system.

The proposed method uses only one network function. However, it gives no ambiguities as demonstrated in the examples.

APPENDIX A

THE COMPUTER PROGRAMS

PROGRAM 1

```
      DIMENSION A(30,50),B(50,50),C(50,50),X(25,2,50),Y(50,30),JJ(50)
      READ(5,111) NV, NR
  111 FORMAT(2I10)
      READ(5,112) (((X(K,L,M),L=1,2),K=1,NV),M=1,NR)
  112 FORMAT(2F10.0)
      WRITE(6,600)
  600 FORMAT(1H1,///)
      WRITE(6,113)
  113 FORMAT(1H0,25X,29HDEFINED BOUNDARY POINT VALUES)
      WRITE(6,114) NV
  114 FORMAT(1H0,25X,26HNUMBER OF FREQUENCIES  NV=,I3)
      WRITE(6,115) NR
  115 FORMAT(1H0,25X,26HNUMBER OF REGIONS      NR=,I3,//)
      WRITE(6,610)
  610 FORMAT(1H0,28X,12HLOWER B.P.V.,3X,12HUPPER B.P.V.)
      DO 10  M=1,NR
   10 WRITE(6,116) ((X(K,L,M),L=1,2),K=1,NV)
  116 FORMAT(1H0,25X,2F15.5/(26X,2F15.5))
      NN=2*NV
      NI=NV+1
      DO 222 I=1,30
      DO 222 J=1,50
  222 A(I,J)=0.
      A(1,1)=1.
      A(NI,1)=100.
      IK=0
      DO 310  K=1,NV
      DO 310  L=1,2
      DO 310  M=1,NR
      IJ=1
      IF(X(K,L,M)+100.)320,310,320
  320 IF(X(K,L,M)-100.)330,310,330
  330 IF(A(K,IJ))340,350,340
  340 IF(A(NI,IJ)+X(K,L,M))350,310,350
  350 IJ=IJ+1
      IF(IJ-IK-1)330,330,360
  360 IK=IK+1
      A(K,IK)=1.
      A(NI,IK)=-X(K,L,M)
```

```
310 CONTINUE
    DO 410  J=1,NR
    DO 410  K=1,NV
    DO 410  IJ=1,IK
    IF(A(K,IJ))420,410,420
420 C(IJ,J)=X(K,1,J)+X(K,2,J)+2.*A(NI,IJ)
    IF(C(IJ,J))440,430,430
430 C(IJ,J)=1.
    GO TO 410
440 C(IJ,J)=-1.
410 CONTINUE
    DO 210  II=1,NI
    DO 210  J=1,NR
    B(II,J)=0.0
    DO 210  IJ=1,IK
    B(II,J)=B(II,J)+A(II,IJ)*C(IJ,J)
    IF(B(II,J))210,220,210
220 B(II,J)=+0.
210 CONTINUE
    WRITE(6,700)
700 FORMAT(1H1,//////////)
    WRITE(6,117)
117 FORMAT(1H0,13X,27HFAULT IDENTIFICATION MATRIX,///)
    IF(NR-10)51, 51, 53
 51 DO 52 II=1,NI
 52 WRITE(6,118) (B(II,J),J=1,NR)
118 FORMAT(1H0,10X,10F8.2)
    GO TO 555
 53 DO 54 II=1,NI
 54 WRITE(6,118) (B(II,J),J=1,10)
    WRITE(6,119)
119 FORMAT(1H0)
    IF(NR-20)55, 55, 57
 55 DO 56 II=1,NI
 56 WRITE(6,118) (B(II,J),J=11,NR)
    GO TO 555
 57 DO 58 II=1,NI
 58 WRITE(6,118) (B(II,J),J=11,20)
    WRITE(6,119)
    IF(NR-30)59,59,61
 59 DO 60 II=1,NI
 60 WRITE(6,118) (B(II,J),J=21,NR)
    GO TO 555
 61 WRITE(6,120)
120 FORMAT(18HOREGIONS EXCEED 30)
    GO TO 999
555 READ(5,300) NM
300 FORMAT(1I10)
```

```
      READ(5,121) ((Y(KK,II),II=1,NI),KK=1,NM)
  121 FORMAT(4F10.0)
      WRITE(6,800)
  800 FORMAT(1H1,////////)
      DO 187 KK=1,NM
      DO 172  J=1,NR
      C(KK,J)=0.0
      DO 172 II=1,NI
  172 C(KK,J)=C(KK,J)+Y(KK,II)*B(II,J)
      IF(KK-1)173,173,174
  173 WRITE(6,122)
  122 FORMAT(1H0,11X,14HVECTOR X      , 20X,15HVECTOR Z       ,//)
  174 WRITE(6,123) (Y(KK,II),II=1,NI)
  123 FORMAT(1H0,7X,10F8.2/(8X,10F8.2))
      WRITE(6,124) (C(KK,J),J=1,NR)
  124 FORMAT(1H0,11X,10F8.2/(12X,10F8.2))
      Z=0.0
      DO 185 J=1,NR
      IF(Z-C(KK,J))181,183,185
  181 DO 182 M=1,NR
  182 JJ(M)=0
      Z=C(KK,J)
      JJ(NR)=J
      MM=NR
      GO TO 185
  183 DO 184 M=2,NR
  184 JJ(M-1)=JJ(M)
      Z=C(KK,J)
      JJ(NR)=J
      MM=MM-1
  185 CONTINUE
      WRITE(6,400) (JJ(M),M=MM,NR)
  400 FORMAT(1H ,40X,27HFAULT IDENTIFICATION REGION,20(I3,1H,)/(49X,20(I
     *3,1H,)))
      WRITE(6,900)
  900 FORMAT(1H0)
  187 CONTINUE
  999 STOP
      END
```

PROGRAM 2

```
      DIMENSION B(30,50),C(50,50),Y(50,30),JJ(50)
      READ(5,111) NI,NR,ND
  111 FORMAT(3I10)
      READ(5,112) ((B(II,J),II=1,NI),J=1,NR)
  112 FORMAT(8F10.0)
      WRITE(6,700)
  700 FORMAT(1H1,//////////)
      WRITE(6,117)
  117 FORMAT(1H0,13X,27HFAULT IDENTIFICATION MATRIX,///)
      IF(NR-10)51, 51, 53
   51 DO 52 II=1,NI
   52 WRITE(6,118) (B(II,J),J=1,NR)
  118 FORMAT(1H0,10X,10F8.2)
      GO TO 555
   53 DO 54 II=1,NI
   54 WRITE(6,118) (B(II,J),J=1,10)
      WRITE(6,119)
  119 FORMAT(1H0)
      IF(NR-20)55, 55, 57
   55 DO 56 II=1,NI
   56 WRITE(6,118) (B(II,J),J=11,NR)
      GO TO 555
   57 DO 58 II=1,NI
   58 WRITE(6,118) (B(II,J),J=11,20)
      WRITE(6,119)
      IF(NR-30)59,59,61
   59 DO 60 II=1,NI
   60 WRITE(6,118) (B(II,J),J=21,NR)
      GO TO 555
   61 WRITE(6,120)
  120 FORMAT(18HOREGIONS EXCEED 30)
      GO TO 999
  555 READ(5,300) NM
  300 FORMAT(1I10)
      READ(5,121) ((Y(KK,II),II=1,NI),KK=1,NM)
  121 FORMAT(8F10.0)
      WRITE(6,800)
  800 FORMAT(1H1,////////)
      DO 187 KK=1,NM
      DO 172  J=1,NR
      C(KK,J)=0.0
      DO 172 II=1,NI
  172 C(KK,J)=C(KK,J)+Y(KK,II)*B(II,J)
      IF(KK-1)173,173,174
```

```
173 WRITE(6,122)
122 FORMAT(1H0,11X,14HVECTOR X       , 20X,15HVECTOR Z        ,//)
174 WRITE(6,123) (Y(KK,II),II=1,NI)
123 FORMAT(1H0,7X,10F8.2/(8X,10F8.2))
175 WRITE(6,124) (C(KK,J),J=1,NR)
124 FORMAT(1H0,11X,10F8.2/(12X,10F8.2))
    Z=0.0
    KC=0
    DO 185 J=1,NR
    IF(Z-C(KK,J))181,183,185
181 DO 182 M=1,NR
182 JJ(M)=0
    Z=C(KK,J)
    JJ(NR)=J
    MM=NR
    GO TO 185
183 DO 184 M=2,NR
184 JJ(M-1)=JJ(M)
    Z=C(KK,J)
    JJ(NR)=J
    MM=MM-1
185 CONTINUE
186 WRITE(6,400) (JJ(M),M=MM,NR)
400 FORMAT(1H ,34X,27HFAULT IDENTIFICATION REGION,20(I3,1H,)/(49X,20(I
   *3,1H,)))
    KC=JJ(MM)
    W=0.0
    U=0.0
    IF(KC-ND)  310, 310, 320
310 NP=ND+1
    DO 385 J=NP,NR
    IF(W-C(KK,J)) 381, 383, 385
381 DO 382  M=NP, NR
382 JJ(M)=0
    W=C(KK,J)
    JJ(NR)=J
    MM = NR
    GO TO 385
383 NT=ND+2
    DO 384 M=NT, NR
384 JJ(M-1)=JJ(M)
    W=C(KK,J)
    JJ(NR)=J
    MM=MM-1
385 CONTINUE
    GO TO 386
320 DO 585  J=1,ND
    IF(U-C(KK,J)) 581, 583, 585
```

```
581 DO 582  M=1,ND
582 JJ(M)=0
    U=C(KK,J)
    JJ(ND)=J
    MM=ND
    GO TO 585
583 DO 584  M=2,ND
584 JJ(M-1)=JJ(M)
    U=C(KK,J)
    JJ(ND)=J
    MM=MM-1
585 CONTINUE
586 WRITE(6,400) (JJ(M), M=MM,ND)
    GO TO 888
386 WRITE(6,400) (JJ(M), M=MM,NR)
888 WRITE(6,410)
410 FORMAT(1H0)
187 CONTINUE
999 STOP
    END
```

APPENDIX B

IMPLEMENTATION OF THE COMPUTER PROGRAMS

INPUT DATA

PROGRAM 1

Card number	Card column	Information	Form
1	1 -- 10	NV number of selected frequencies	integer
	11 -- 20	NR number of fault identification regions	"
2	1 -- 10	lower B.P.V. of x_1 for fault identification region R-1	decimal
	11 -- 20	upper B.P.V. of x_1 for fault identification region R-1	"
3	1 -- 10	lower " x_2 "	"
	11 -- 20	upper " x_2 "	"
NV+1	1 -- 10	lower " x_{nv} "	"
	11 -- 20	upper " x_{nv} "	"
NV+2	1 -- 10	lower " x_1 " identification region R-2	"
	11 -- 20	upper " x_1 " identification region R-2	"
2NV+1	1 -- 10	lower " x_{nv} "	"
	11 -- 20	upper " x_{nv} "	"

2NV+2	1 -- 10	lower " x_1 " identification region R-3	"
	11 -- 20	upper " x_1 " identification region R-3	"
NR·NV+1			
NR·NV+2	1 -- 10	NM number of measurements	integer
NR·NV+3	1 -- 10	magnitude value of x_1	decimal
	11 -- 20	" x_2	"
	21 -- 30	" x_3	"
	NV	1.	
NR·NV+4	1 -- 10	magnitude value of x_1	"
	11 -- 20	" x_2	"
	NV	1.	
NR·NV+2+NM			

PROGRAM 2

Card number	Card column	Information	Form
1	1 -- 10	NI number of M rows	integer
	11 -- 20	NR number of M columns	"
2	1 -- 10	entry of col-1, row-1 of M	decimal
	11 -- 20	" row-2 "	"
	21 -- 30	" row-3 "	"
		row-ni "	"
3	1 -- 10	entry of col-2, row-1 of M	"
	11 -- 20	" row-2 "	"
		row-ni	"
NR+1			
NR+2	1 -- 10	NM number of measurements	integer
NR+3	1 -- 10	magnitude value of x_1	decimal
	11 -- 20	" x_2	"
	NV	1.	
NR+4	1 -- 10	magnitude value of x_1	"
	11 -- 20	" x_2	"
	NV	1.	
NR+2+NM			

* Open end value may be used +100. for upper boundary and 0. for lower boundary.
* Appropriate modification may be done.

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13. ABSTRACT

A method utilizing vector representation is investigated for determining a faulty element in passive and active networks by simple external measurements.

A large system may be considered as an interconnection of a number of sub-networks. By utilizing the relationships between the magnitudes of a transfer function at various frequencies and the deviations of a circuit element, the fault simulation curves can be drawn. The fault identification regions are defined from the fault simulation curves. A fault identification matrix is constructed corresponding to the defined fault identification regions.

The fault identification matrix, when premultiplied by a vector whose components are measured from a network, yields another vector whose components identify a network element which is faulty.

A test procedure for the fault identification method is presented and verified.

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